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Study of natural gas vehicles (NGV) during the fast fill process

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ABSTRACT

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Natural gas is being used as an alternative fuel to gasoline. Natural gas vehicle (NGV) refueling stations, however, are not able to guarantee a 100% full fill to NGV's. A system was designed and built to better understand the characteristics of CNG during the fill process. Useful characteristics of CNG during the fill process are temperature, pressure, and flow rate, as well as, total volume dispensed. CNG is dispensed to an NGV through a process known as the fast fill process, since it is completed in less than five minutes. The system that was built is transportable, which means that it can be used for testing at any NGV refueling station. The information that the transportable test rig provides can be used to acquire information about the fast fill process, which can be used by NGV station manufacturers to design a system that can, possibly, guarantee a 100% NGV fill level.

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1 Introduction

An alternative fuel to gasoline and diesel fuel for automobile use is an issue that we, the human race, can ill afford to ignore any longer. As Americans, the quality of air in our large metropolitan areas is becoming ever worse at an alarming rate. This will not be an easy task to achieve. Gasoline and diesel fuel are the most readily available sources of fuel for automobiles in the United States with gasoline being the dominant fuel used in passenger cars. An overwhelming majority of all vehicles are manufactured to operate exclusively on gasoline or diesel fuel.

An alternative to using gasoline and diesel fuel is the use of natural gas. Natural gas is a clean burning fuel that emits far fewer emissions than gasoline or diesel fuel. Natural gas is also a readily available natural resource found in the United States and across North America. This would make the U.S. far less dependent on foreign countries for petroleum.

One of the largest hurdles to overcome to make natural gas a publicly accepted alternative to gasoline and diesel fuel, is the lack of natural gas refueling infrastructure. Currently, there are very few natural gas refueling stations in operation in the U.S. compared to the number of gasoline refueling stations. A person could be all for making a difference in the environment by purchasing a natural gas vehicle (NGV), but without anywhere to refill it, it seems like a very poor financial decision. Even if a person lives in a community with a few natural gas refueling stations, that person may not have another refueling station within' a the vicinity of the community. That issue makes a strong statement against the use of an NGV for someone that has to do a lot of traveling. The industry is striving to build more CNG refueling stations with federal and state governments giving tax breaks to NGV consumers and companies that build CNG refueling stations.

Another problem hindering a wide range of acceptance is the low driving range compared to gasoline vehicles. This low driving range is very unappealing to most car purchasers. CNG storage on an NGV takes up a lot of onboard space to create a sufficient onboard fuel storage bank. The storage cylinder(s) on an NGV are bulky (a 2 GGE Brunswick® CNG storage cylinder is 9.2" x 35"). Two gasoline gallon equivalent (GGE) of CNG will not permit a very far driving range for an NGV of any size. If a person is utilizing a Honda Civic that gets 33 miles per gallon, only 66 miles of driving range could be possible. Many cylinders can be linked together to form a larger control volume, but the NGV has to sacrifice vehicle space to compensate for extra fuel storage.

Zooming in on the reduced driving range for NGV's heads the bulk of the research done for this report. The information in this report illustrates the temperature, pressure, and flow rate of CNG during a 'rapid charge' or 'fast fill' (a comparable time to fill a gasoline vehicle, generally <5 minutes) at separate ambient temperatures. An approximation was made on the percentage of a maximum fill of the vehicle CNG fuel cylinder(s) or fuel storage tank, which is a positive start in the design of an improved system that will ensure that the NGV onboard CNG fuel storage cylinder(s) receive a 100% full fill every time the NGV fuel storage system is replenished. Even the most advanced natural gas refueling stations can only guarantee a 92% - 98% full fill.

2 Review of Relevant Literature

Over the last few decades it has been acknowledged that an alternative fuel to gasoline needed to be developed. Alternative fuels need to be used more for automobile use for their obvious emissions benefits, but also as a tool for the United States to become less dependent on the oil imported from foreign countries. Although natural gas is a hugely available resource in the United States, it has not been widely accepted as an alternative fuel to gasoline by the general public. Some of the obvious reasons are the lack of natural gas refueling stations (infrastructure) and the low driving range of NGV's (compared to gasoline).

A problem with NGV refueling stations in the past was the amount of time used to refuel an NGV. The NGV industry has made excellent advancements in the industry to provide a system to refuel and NGV in a comparable to that of a gasoline dispenser. The problem with the long refueling time has been remedied for the most part to be comparable to the fill time (< 5min) taken to fill a gasoline powered automobile. This (<5 min) fill time can be referred to as a 'fast fill' or 'rapid charge'. The fast fill process has brought some problems to the surface concerning under filling the compressed natural gas (CNG) vehicle storage cylinders, safety issues, and other problems, which will be discussed in the following paragraphs.

2.1 Emissions Benefits of NGV's

The emissions from a normal NGV are far lower than emissions from a gasoline fueled vehicle. "Compared with most gasoline powered vehicles, dedicated NGV's typically reduce exhaust emissions CO by approximately 70 percent, non-methane organic gas (NMOG) by 89 percent, and NO_x by 87 percent. NGV's also emit virtually no particulate matter emissions, a pollutant that increasingly has come under scrutiny from health officials and air quality officials. NGV's are here today and have repeatedly demonstrated their ability to surpass even the most demanding new emission requirements. These vehicles are not prototype vehicles rather they are production line vehicles ready for delivery now. NGV's come in a variety of makes and models, including passenger cars, pickup trucks, school and urban buses, and heavy-duty trucks (NGVC, [1])."

Metropolitan areas are being saturated with pollutants produced by on-road vehicles. An alternative to gasoline and diesel has to be considered for a better environment. "Cars, vans, trucks and buses, and other on-road vehicles using traditional fuels produce more than 60 percent of all carbon monoxide (CO) pollution. They also are the second largest national source of hydrocarbons (HC's) at 29 percent and nitrogen oxides (NO_x) at 31 percent, the major ingredients of unhealthful ground-level ozone. In many urban areas, motor vehicles are the single largest source of major criteria pollutants. Motor vehicles also emit more than 50 percent of all hazardous air pollutants. Of 112 million Americans living in areas with air that is unhealthy to breathe, 100 million live in areas that fail to meet the air quality standards for ground-level ozone (NGVC, [2]).”

In addition to the obvious emissions benefits during the combustion of natural gas, it also does not produce any evaporative emissions. When fueling an NGV, the connection of the NGV to the dispenser is sealed so that no CNG escapes to the atmosphere. Whereas gasoline dispensers do not make a sealed connected to the vehicle being fueled which allows for evaporative emissions to take place. “In gasoline vehicles, evaporative and fueling emissions account for at least 50 percent of a vehicles total hydrocarbon emissions (NGVC, [3]).”

2.2 National Energy Security

The United States is far too dependent upon foreign oil. The U.S. has far too much natural gas to be so dependant upon petroleum as its only form of fuel for on-road vehicles. Americans could help the U.S. become less dependant upon foreign oil if its citizens would consider converting to natural gas as an alternative fuel to gasoline and diesel. “For several years now, the United States has imported more than 50 percent of the oil it uses (approximately 57 percent in 2001). Future projections by the Energy Information Administration (EIA) predict that oil imports will continue to increase as domestic consumption continues to outpace U.S. production. Consequently, U.S. imports of foreign oil account for 59 percent of the oil consumed. This number is expected to grow to 72 percent by 2010. Roughly 67 percent of the oil we use goes for transportation. The U.S DOE has recently stated that there is a one for one correlation between increased demand for transportation fuels and oil imports. Much of the increase in oil imports will come from OPEC members and Persian Gulf countries. On the other hand, the natural gas that is consumed in the U.S. comes mostly from domestic supplies. Nearly 87 percent of all natural gas consumed in the United States is domestically produced, and almost all of the remainder is produced in Canada. Using North American natural gas instead of oil or other fuels imported from overseas improves energy security and the U.S. balance of trade (NGVC, [4]) ."

2.3 Incentives of NGV's

The government has tax breaks available to the consumer and to the company that promotes the alternative fuel industry. The government is aware that the U.S. will become less dependent upon foreign oil if alternative fuels that are native to North America are accepted by Americans as well as decrease emissions from road vehicles. "Tax incentives for new technology and alternative fuel vehicles under this legislation go directly to the consumer. To ensure that these technological advances put priority on fuel economy improvements and support the overall objectives to improve energy security and diversity, performance incentives have been incorporated in order for a vehicle to be eligible for the tax credits. These performance incentives are added to a base credit that is provided for introducing the technologies into the marketplace (NGVC, [5]) ."

2.3.1 Incentives to the Consumer

The government is striving to make natural gas vehicles appealing to the general public. The government understands that it will benefit as well as the environment if the citizens of the United States can consider moving to CNG as an alternative fuel to gasoline and diesel. State and Federal governments have incentives available to people and companies that promote the use of CNG. "Vehicles solely capable of running on alternative fuels promote energy diversity and significant emission reductions. Natural gas, LPG and LNG are the most commonly used fuels for dedicated alternative fuel vehicles. A base credit of up to $2500 is included with an additional $1500 for vehicles certified to "Super Ultra Low Emission" standards (SULEV). Note that "flex fuel" vehicles are not included since they can operate on either gasoline or E85 (ethanol) and are available n the market without any incremental cost (NGVC, [6])."

"The NGV market place in the United Sates is in a growth period. This is due, in part, to Federal Government mandates requiring staged fleet conversion to alternative fuels. The growth of the NGV market depends upon: (1) vehicle availability at a reasonable cost, and (2) development of a fueling infrastructure. Presently, there are several programs actively supporting the development of natural gas fueled vehicles (Barajas, et al, [7])."

2.3.2 Incentives for Improving Alternative Fuel Infrastructure

"Complementary to the credit for the fuel itself, the existing $100,000 tax deduction is extended for 10 years and a credit for actual costs up to $30,000 for the installation cost of alternative fuel sites available to the public is included. One of the key hurdles to overcome in commercializing alternative fuel vehicles is the lack of fueling infrastructure. For nearly a century, infrastructure has focused primarily on gasoline and diesel products. The fuel incentive will help the distributors overcome the costs to establish the alternative fuel outlets and support distributors during initial lower sales volumes as the number of alternative fuel vehicles increases (NGVC, [8])."

2.4 NGV / CNG Safety

Safety is always a concern for any application. NGV's and NGV components are put through severe test procedures to ensure that safety concerns are made accountable. A few comparisons of CNG and NGV's to gasoline and gasoline automobiles are discussed in the rest of this paragraph. "CNG, unlike gasoline, dissipates into the atmosphere in the event of an accident. Gasoline pools on the ground creating a fire hazard. The fuel storage cylinders used in NGVs are much stronger than gasoline fuel tanks. The design of NGV cylinders are subjected to a number of federally required "sever abuse" test, such as heat and pressure extremes, gunfire, collisions and fires. Natural gas has a high ignition temperature, about 1,200 degrees Fahrenheit, compared with about 600 degrees Fahrenheit for gasoline. It also has a narrow range of flammability that is, in concentrations in air below about 5 percent and above about 15 percent, natural gas will not burn. The high ignition temperature and limited flammability range make accidental ignition or combustion of natural gas unlikely. Natural gas is not toxic or corrosive and will not contaminate ground water. Natural gas combustion produces no significant aldehydes or other air toxins, which are a concern in gasoline and some other alternative fuels (NGVC, [9])."

2.5 Attributes of Natural Gas

Attributes of natural gas are important facts to know in order to better compare and contrast the differences between natural gas and gasoline. "Natural gas typically consists of about 90 percent methane (CH_4). The emissions from natural gas vehicles also are primarily unburned methane. Methane is not a volatile organic compound (VOC). This is important because unburned and evaporative VOCs combine with oxides of nitrogen (NO_X) in the presence of sunlight to form ground level ozone. Although methane is a greenhouse gas (and, in fact, is a more intense greenhouse gas than carbon dioxide), natural gas vehicles on the whole contribute less to greenhouse gas formation because natural gas has less carbon than gasoline and other petroleum motor fuels. Gasoline and diesel fuels and their exhaust contain numerous harmful chemical agents. The gaseous components of diesel exhaust, for example, contain benzene, 1,3-butadiene, arsenic, and nickel, which are known to cause cancer in humans.

The fuel cycle emissions of natural gas are much less than other transportation fuels. Fuel cycle emissions include emissions that occur during energy extraction, processing, conversion, transportation and distribution. Because it generally is not refined or transported by truck or barge, natural gas does not pose nearly the transportation related environmental and safety hazards associated with gasoline and diesel.

As a motor fuel, natural gas provides superior emissions performance relative to gasoline and diesel. Among the reasons for this are that NGVs: have virtually no evaporative and running loss emissions due to their sealed fuel systems and negligible refueling emissions, have inherently lower non-methane hydrocarbon (NMHC) emissions since the fuel is 85-99 percent methane, emit significantly less toxic air contaminants such as benzene and 1,3 butadiene since these chemicals and their precursors are not found in natural gas, have lower "off cycle" emissions, have lower cold-start emissions, and have better emission durability due to the reduced complexity of their emission control system (NGVC, [10])."

2.6 Local and National CNG Refueling Infrastructure

As previously mentioned, NGV fueling infrastructure is extremely important for the future of the NGV market. In order for an NGV to be appealing to 'Joe consumer' there have to be sufficient CNG refueling stations. Again, if an NGV owner only has one station in the community he/she lives in with the closest 'out of station' being 30-40 miles or more away that could be a huge nuisance when needing to refuel.

An investigation was compiled to determine the number of fueling stations in the Morgantown and Pittsburgh areas. The stations are shown geographically with a 25 mile radius around the central business district of each respective city. The stations located within a 25mile radius of Morgantown, WV are illustrated in Figure 2.6-1. All stations located within 25 miles of Pittsburgh, PA are illustrated in Figure 2.6-2. The location of the CNG refueling stations are denoted by red triangles. A U.S. map containing information on the location/counts for CNG is illustrated in Figure 2.6-3. Information about the CNG station location relative each particular city as well as the U.S. map indicating CNG location/count was also found on the Alternative Fuels Data Center (AFDC) website (AFDC, [11]).

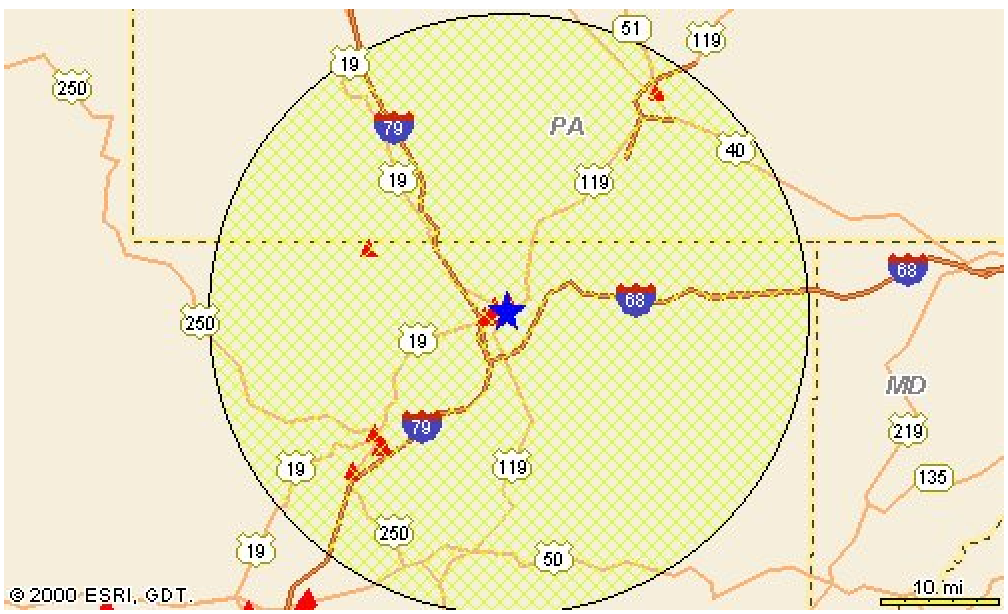


Figure 2.6-1CNG refueling Stations within 25 miles of Morgantown, WV.

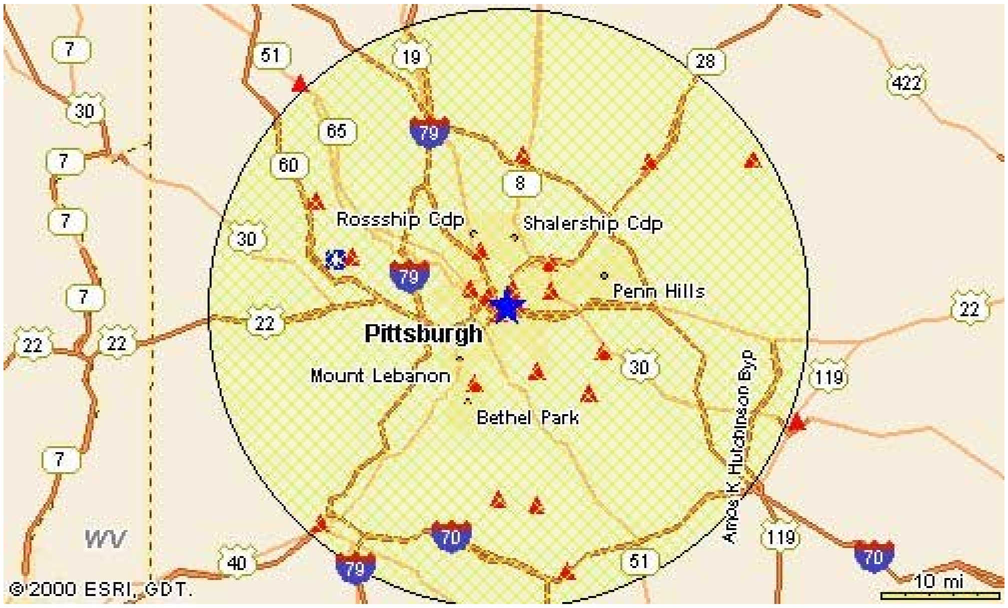


Figure 2.6-2 CNG Refueling Stations Within 25 Miles of Pittsburgh, PA.

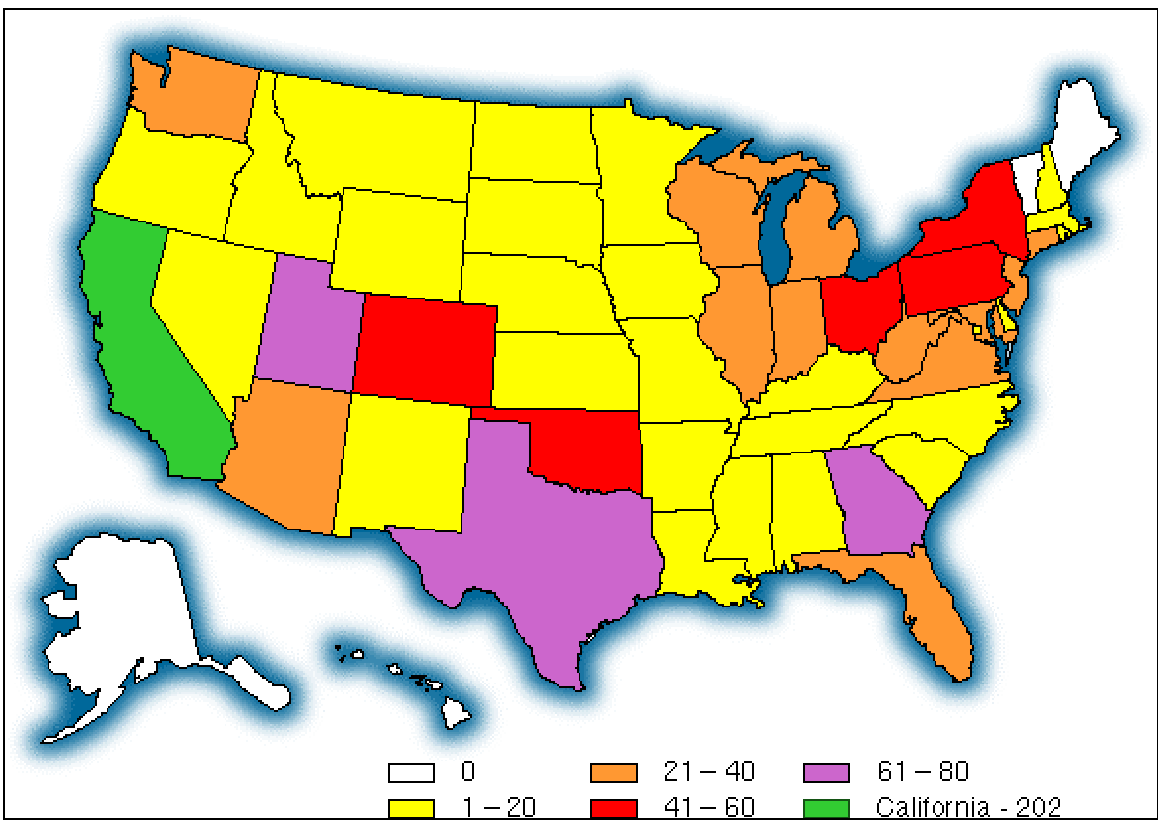


Figure 2.6-3 U.S. Map Showing Refueling Station Locations/Counts for CNG

2.7 A Comparison of an NGV and a Gasoline Fueled Automobile

A comparison of a gasoline fueled vehicle and a natural gas powered vehicle is useful information. The automotive industry can compare and contrast the two styles of vehicles to determine optimal values in which to compare the two vehicles. Research was done on two automotive manufacturers and models: the Honda Civic and the Ford Crown Victoria. The information attained was a comparison of: fuel type, fuel economy (city, highway, and combined), annual fuel cost, annual greenhouse gas emissions, EPA size class, engine liters, passenger volume, and luggage volume (notice the reduction for each CNG vehicle to compensate for fuel storage cylinders). The information was provided by the U.S. Department of Energy web site (U.S. DOE, U.S. EPA, [12]). The comparison is shown in Table 2.7-1.

Category	2002 Honda Civic	2002 Honda Civic (CNG)	2002 Ford Crown Victoria	2002 Ford Crown Victoria (CNG)
Fuel Type	Gasoline	CNG	Gasoline	CNG
MPG (city)	*31*	*30*	*17*	*15*
MPG (highway)	*38*	*34*	*25*	*22*
MPG (combined)	*34*	*32*	*20*	*18*
Annual Fuel Cost ($)	*622*	*656*	*1058*	*1167*
Annual Greenhouse Gas Emissions	*5.7 tons*	*5.1 tons*	*9.5 tons*	*8.9 tons*
Engine size (liters)	1.7	1.7	4.6	4.6
Passenger Volume (ft^3)	91	91	111	111
Luggage Volume (ft^3)	*13*	*7*	*21*	*16*

Table 2.7-1 Comparison of two vehicle makes and models of CNG and Gasoline.

2.8 An Overview of the Current Status of NGV Refueling Station Technology

CNG dispensers perform similar functions to gasoline dispensers in that they control the fuel flow, measure the amount of fuel dispensed into the vehicle, and compute the sale amount. Although the newest CNG technology has allowed the average CNG refueling time to be reduced to less than five minutes for most passenger vehicles, improvements still need to be made to make the fill time comparable to a gasoline fill time. "The specific areas where improvements are required include: reducing the dispenser cost, improving the dispensed gas flow measurement accuracy, reducing the time required to fill the vehicle, and increasing the level of fill provided by the dispenser control system (Barajas, et al, [13]).”

The on-board storage capacity of natural gas vehicles (NGV) defines the driving range allowable before refueling is required. Under filling of NGV gas storage cylinders, during fast fill (<5 minutes) charging operations, can occur at fueling stations having dispensers which are incorrectly or inaccurately compensated for initial cylinder pressure and temperature, station supply gas pressure and temperature, and ambient temperature. At higher ambient temperatures, i.e. 85^{o}F and above, and under direct station compressor outlet charges of the NGV cylinder, this under filling can reach 15% - 20% or more of the rated gas mass storage capacity of the NGV cylinders. This under filling is a serious marketing obstacle for NGV’s to overcome, without resorting to unnecessarily high fueling station gas storage pressures, or by applying extensive over pressurization of the vehicle cylinders during the fueling operation.

“Each unit of supply gas, which enters the cylinder, has enthalpy, i.e. not only the internal energy of the gas in the supply, but also the supply “pv” work, associated with its flow. Note also that the gas in the cylinder volume contains only internal energy. One of the reasons behind the temperature rise of the gas in the cylinder, during a fast fill operation, lies in this conversion of enthalpy into internal energy.”

“When charging a nearly full cylinder, the gas temperature profile is monotonic, reaching successively lower final values, as the initial pressure of the cylinder gas increases. The reason for the dip in temperature, in the early part of the filling of a nearly empty cylinder, lies in the Joule-Thomson cooling effect, which the gas undergoes in the isenthalpic expansion through the orifice, from the 3000 psia supply pressure to the initially low 100 psia cylinder pressure. This cold gas mixes with and compresses the gas originally in the tank, with the result that the combined mixed gas temperature initially reduces. When the compression and conversion of supply enthalpy energy to cylinder internal energy overcomes the Joule-Thompson cooling effect, which becomes smaller as the cylinder pressure rises, the mixed gas temperature in the cylinder begins to rise. If the initial gas pressure in the cylinder is relatively high, the Joule-Thompson cooling effect is smaller, and does not, at any time, overcome the supply enthalpy conversion to cylinder internal energy. In this case, the cylinder gas temperature is seen to rise monotonically."

"NGV fueling stations must take into account at least ambient conditions when recharging cylinders to maximize the range of the vehicle, while at the same time avoid overcharging, with its possible safety problems. As an example, if the ambient were 70^{o}F, to achieve a cooled cylinder pressure of 3000 psia, the cylinder would need to be fast charged to about 4000 psia, if the supply gas were at 5000 psia. If the ambient were 100^{o}F, the cylinder would need to be charged to about 4600 psia, to achieve the rated mass level. This dynamic over pressurization is a source of design difficulty for not only the NGV cylinder manufacturer, but also for the fueling station manufacturer and operator, since the fueling station compressor discharge and ground storage would need to be at least 5000 psia, to ensure a fully charged cylinder at high ambients
(Kountz, [14])."

Undercharged cylinders, during fast fills, are partially the result of the fueling station dispenser control system either ignoring, or inaccurately estimating, the elevated NGV storage cylinder gas temperatures, which occur in the charging period, due to compression, mixing, and other complex and transient thermodynamic processes. During charging, the expansion of the gas from the station ground storage reservoirs, or directly from the station compressor outlet, does reduce the temperature of the gas entering the NGV cylinders due to the Joule-Thomson effect, which occurs during this essentially constant enthalpy process. However, the gas in the cylinder converts this entering gas enthalpy to internal energy, and undergoes complex and dynamic compression and mixing processes, which overcome the cooling effect of the entering gas. In fact, gas cooled by expansion before entering the vehicle cylinder gains heat when flowing through pipes and can result in higher end-of-fill temperatures and reduced fills.

The NGV industry is using a universal style CNG storage cylinder used on NGV's. Having a common cylinder pressure rating design provides a common design criteria for current dispenser technology to meet. "Currently, NGV storage cylinders in service have nominal rating pressures at the 3000 and 3600 psig levels, and depending on the specification of the manufacturer, have various levels of allowable maximum fill pressures. This is normally 125% of the nominal rating (Kountz, [15])."

The pressure in a cylinder can change as the ambient temperature changes. This is a safety concern. One concern is if a vehicle goes through the fast fill process on a cold day then is put into a garage at a room temperature will the pressure rise due to ambient rise cause the cylinder to develop a pressure greater than design. Changes in temperature will cause CNG pressure in the cylinder to vary. The chart below (Table 2.8-1) indicates the relationship between temperature and cylinder pressure

(Hutton, [16]). The information shown in Table 2.8-1was from tests compiled on DOT 3AA 2400# cylinders.

Figure 2.8-1 displays the nearly linear relationship of ambient temperature versus cylinder pressure. This relationship is important to know. For example, if a cylinder is filled on a day in which the ambient temperature is 0°F and then taken into a shop at 70°F for maintenance reasons the cylinder pressure will increase significantly. And a counter example could be filling a cylinder on a hot day, and then not using the NGV until a colder day arrives. This delayed use of the NGV will directly reduce the driving range of the vehicle because of the reduced pressure left in the tank.

Temperature (°F)	228	170	130	100	70	40	0	-30
Pressure (psig)	3000	2868	2737	2606	2475	2344	2214	2083

Table 2.8-1 Relation of Ambient Temperature Change and Cylinder Pressure.

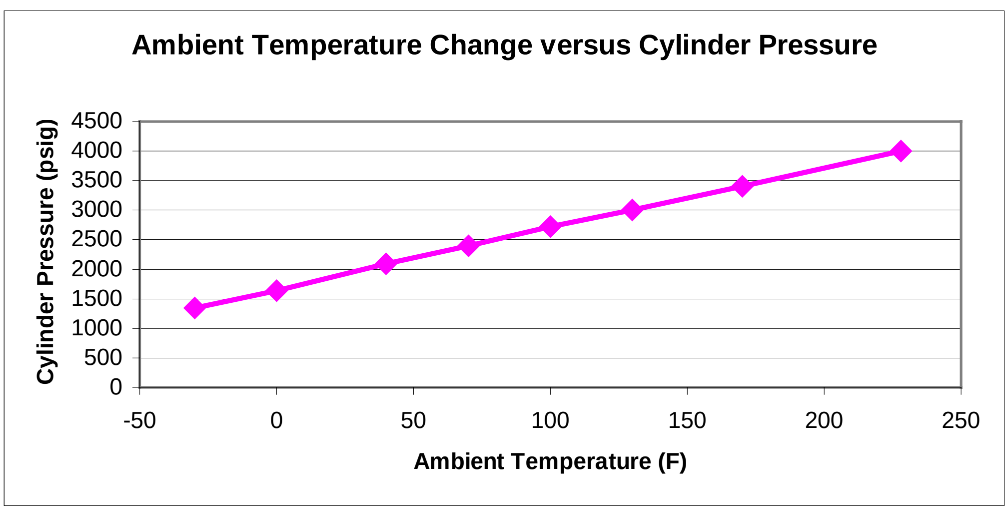


Figure 2.8-1 Relationship Between Ambient Temperature Change and Cylinder Pressure

One opportunity, to alleviate the need for creating and storing such high pressures in the fueling station, lies in the cooling of the supply gas, if a practical and cost effective way could be developed[iii][3].

The highest gas pressures in a vehicle storage tank will occur during fast filling operations, which are accomplished at high ambient temperatures. During a fast fill operation to the maximum 4500 psig level allowable in the NGV2 standard, the greatest combination of cylinder wall stress conditions due to gas pressure and cylinder wall temperature differences will occur (Kountz, [17]).

"At the low ambient temperature extremes, engine fueling operations of NGV storage cylinders can result in extremely low gas temperatures. Gas temperatures as low as -70^{o}F have been measured, after a 2 hour discharge, at a rate of 3 SCFM (1.45 equivalent gasoline gallons per hour), after starting the discharge from a fully charged cylinder at -25^{o}F."

"At low ambients, since gas from the vehicle storage cylinder will undergo further temperature reductions when expanding through engine fueling system components, such as pressure regulators, carburetors or fuel injectors, etc. these components will need to be functional while operating on extremely low temperature gas. If the gas expands isenthalpically, i.e. without heat transfer, from the vehicle storage cylinder through the engine fueling components, it can be expected that at least some of the higher hydrocarbon components, i.e. ethane, propane, etc. which are normally present in natural gas, will condense somewhere in the cylinder and/or the fueling system. Special precautions to provide gas heating, i.e. via engine coolant or other means to certain of these engine components may be needed to prevent problems relating to these condensates.”

“It is recommended that low ambient temperature (-40^{o}F) tests be made on actual engine fueling system mockups, with the gas supplied from vehicle gas storage cylinders. These tests would support the definition of low ambient temperature performance standards for fueling systems and components[iv][14].”

3 Problem Statement

One of the largest problems on NGV fueling station technology is the inability to provide a 100% full fill to a CNG storage cylinder without over-pressurizing the onboard storage cylinder(s). Even some of the most advanced systems on the market can only guarantee a 92-98 % full fill (Greenfield Compression Inc.) which include complex computer control algorithms to estimate the total pressure and temperature of the CNG dispensed to a storage cylinder(s).

When driving range is already reduced when using CNG because of the decrease in fuel economy and reduced onboard storage space to for CNG storage due to the bulky nature of the CNG storage cylinders, it is very important for CNG refueling stations to provide a 100% full fill. Without directly measuring the in cylinder temperature, it is extremely difficult to estimate the internal cylinder temperature on an NGV being serviced even with the most advanced computer control algorithms available on the market today. A method of determining this 'internal cylinder temperature' has been developed for this report (discussed in Chapter 5).

It is important to understand what is happening to the CNG during the fast fill process to better understand what is occurring through out the duration of the fill process. A test manifold was developed which measures temperature, pressure, flow rate, and accumulation of CNG volume dispensed to an NGV.

The determination of temperature, pressure, flow rate and/or volume, as well as the monitoring of the CNG storage cylinder internal temperature is important information to know during the process. Knowing the value of the entities mentioned provides information on the fill process as it is occurring. The information can be used to better help in the design or improvement of existing systems or the creation new systems that will ensure a 100% full fill every time an NGV needs to be filled with CNG. The system is transportable, which allows the system to be taken to any station that may have the desire to see how efficiently their particular fueling station is operating. A detailed description of the experimental test setup is provided in Chapter 5 of this report.

4 Mathematical and Computer Backing

4.1 STRAPP computer program

Mathematical support was used to give a theoretical backing to the data collected in this report. A theoretical or mathematical backing is achieved through the use of a computer program written by the National Institute of Standards and Technology (NIST). The computer program written by NIST is called STRAPP.

This project is based on the transmission of natural gas. When dealing with a real gas (natural gas), the gas does not obey ideal gas laws. The molecules of natural gas behave in a manner that is more complex than a typical 'ideal' gas. A compressibility factor for natural gas must be applied to correct the ideal gas law for use with natural gas. An effective means of computing the compressibility factor for CNG was important for this project. The compressibility factor had to be determined to help evaluate the theoretical amount of natural gas dispensed to the fuel storage cylinder used in this project. The STRAPP computer program was used to calculate the compressibility factor of the natural gas at several different temperatures and pressures. The compressibility factor does not have a linear relationship to the temperature and pressure increase during the fast fill process, which is why the STRAPP computer program was used.

The STRAPP program was simple to execute. STRAPP was executed in the Disk Operating System (DOS). STRAPP was executed after a few required pieces of information were entered during the input section of the program. The information required by STRAPP is the mole fraction of each component or compound present in natural gas and the temperature (Kelvin) and the pressure (bar) of the natural gas. The components of the natural gas are assumed to be equivalent to that of the national average for natural gas composition. An illustration of the U.S. average of each component present in natural gas is shown in Table 4.1-1.

Constituent	Mole %
Methane	92.87
Ethane	3.34
Propane	0.63
I-Butane	0.07
N-Butane	0.12
I-Pentane	0.04
N-Pentane	0.03
N-Hexane	0.05
Nitrogen	2.07
Carbon Dioxide	0.78

Table 4.1-1 The composition of the mean U.S. natural gas mixture.

The temperature and the pressure inputted to STRAPP is the temperature and pressure present inside the fuel storage cylinder at any particular time contained in the time range it takes for the fill process to be completed based upon the ambient temperature the day the test fill was performed. The temperature and pressure inside the storage cylinder is dependent upon ambient temperature. For this project, the final temperature and pressure of the fast fill process was inputted to STRAPP. STRAPP calculated the compressibility factor for each temperature and pressure combination entered into the program.

4.2 Thermodynamics of the process

Once the compressibility factor was computed using STRAPP, it was possible to use thermodynamic relationships to estimate the total amount of fuel dispensed to the test cylinder. The simplest method, mathematically, to correct the ideal-gas equation so that it predicts real-gas behavior is to write it in the format as in Equation 4.2-1 (Wark, [18]).

Equation 4.2-1 $$PV = ZmRT$$

Where P is the pressure present inside the tank, V is the water volume of the test cylinder (a detailed description of the tank is given in Table 5.4-1), Z is the compressibility factor (found using STRAPP), m is the mass of the CNG present in the tank, R is gas constant ($R = R_u / M$; where R_u = Universal Gas Constant and M = molar mass of natural gas), and T is the temperature inside the tank. Equation 4.2-1 was rearranged to evaluate the mass of CNG dispensed to the cylinder. Using the aforementioned information from Equation 4.2-1 a sample calculation was executed to illustrate the first step in calculating the theoretical volume of gas dispensed to the test cylinder at a 77^{o} F ambient temperature.

Mass of CNG dispensed to test cylinder on a 77^{o} F ambient day (application of Equation 4.2-1):

P = pressure inside tank (or test cylinder) = 2653.90 psi = 382,161.60 psf

V = water volume of tank = 0.83 cubic feet (ft^3)

Z = compressibility factor (unit-less) = 0.85

R = gas constant = Ru / M = [1545 ft * lb$_f$ / (lbmol * R^o)] / [17.034 lbm / lbmol] = 89.30 =(ft * lb$_f$) / (lb$_m$ * R^o)

T = temperature inside tank = 569.30 ^{o}R = 109.60 ^{o}F

So, the mass of the CNG dispensed to the cylinder was:

$$\mathbf{m = PV / ZRT = 7.32\ lb_m \pm \Delta m}$$

Where Δm is the uncertainty of the instrumentation. "Finding the uncertainty in a result due to uncertainties in the independent variables is called finding the propagation of uncertainty (Beckwith, [19])." The propagation of uncertainty is found using:

$$\sigma_y = \sqrt{(\partial y/\partial x_1 \bullet \sigma_1)^2 + (\partial y/\partial x_2 \bullet \sigma_2)^2 + \ldots + (\partial y/\partial x_n \bullet \sigma_n)^2} \cdot$$

The propagation of uncertainty equation was broken down to involve variables present in the data acquisition of the system. The propagation of uncertainty equation **(**Equation 4.2-2) when taking the uncertainty in the measurement devices into account resembles the following**:**

Equation 4.2-2 $$\Delta m = \sqrt{(\partial m / \partial p \bullet \Delta p)^2 + (\partial m / \partial T \bullet \Delta T)^2}$$

Where m is the mass of natural gas dispensed to cylinder, p is the pressure inside the cylinder, T is the temperature inside the cylinder, and the derivatives of mass with respect to p and T were also calculated and entered into the equation.

Calculation of the uncertainty was found using the variables present for the calculation of the mass in the cylinder at the end of the fill process (propagation of uncertainty equation (Equation 4.2-2), assume the same independent variable values as used previously):

$\partial m / \partial T$ = (-V * P) / (Z * R * T^2) = -(.83 ft^3 * 382,161.60 psf) /

[.85 * 89.30 (ft * lb_f / lb_m * R^o) * ((569.30) $R^o)^2$] = -0.013 lb_m / R^o

$\partial m / \partial p$ = V / (Z * R * T) = .83 ft^3 / [.85 * 89.30 (ft * lb_f / lb_m * R^o) * 569.30 R^o]

= 1.93 * 10^{-6} (lb_m * ft^2) / lb_f

ΔT = instrument resolution for temperature = +/- 4.27 F^o = +/- 13.54 R^o

Δp = instrument resolution for pressure = +/- 3.051 psi = +/- 439.34 psf

So, Δm (uncertainty) for the mass calculation was determined to be:

$$\Delta m = \sqrt{(\partial m / \partial p \bullet \Delta p)^2 + (\partial m / \partial T \bullet \Delta T)^2} = \text{+/- } 0.18 \text{ lb}_m$$

Upon determining the mass of the CNG compressed into the storage cylinder and determining the uncertainty involved in the instrumentation, it was possible to calculate the volume of the CNG dispensed in terms of GGE (Gasoline Gallon Equivalent). A conversion factor (5.66 lb_m = 1 GGE) makes it possible to convert the mass of CNG present inside the test cylinder to GGE, which is the industry standard. Using the conversion factor previously mentioned, it was possible to determine the volume of CNG injected to the test cylinder in units of GGE. The conversion is shown below:

Volume = 7.32 lb_m +/- 0.18 lb_m* (1 GGE / 5.66 lb_m (natural gas))

= 1.29 +/- 0.03 GGE

Knowing that the maximum capacity of CNG allowed in the test cylinder (2 GGE), it was possible to determine that the test cylinder was under filled. Knowing that the volume of CNG injected was 1.29 GGE and the maximum capacity of the cylinder was 2 GGE (at 3600 psi and 70^o F) the test cylinder for the 77^o ambient day was under filled by approximately 35.5 %. A detailed description of the test cylinder is provided in Section 5.4 of this report. A 35.5 % under fill indicates one of many concerns for the future of NGV refueling systems and public acceptance.

Note, the NGV refueling system at the physical plant is setup to fill vehicles with 3000 psi and 70^o F rated fuel storage cylinders rather than the 3600 psi and 70^o F level. That information indicates that because a 3600 psi rated cylinder is being used instead of a 3000 psi rated cylinder for testing that a full fill would not be possible anyway.

4.3 GASDEN computer program

It was important to determine the density of the CNG in the manifold in order to correctly measure flow rate in Gasoline Gallon Equivalent per Minute (GGE/min). It was also useful to know the density of the CNG to determine the specific gravity of the natural gas, which is a comparison to the density of water at separate temperatures. The importance of the determination of the CNG density is described in greater detail in section 5.3.6 of this report. The density of the CNG in the manifold at every sample taken by the data acquisition system, which is assumed to be uniform throughout the manifold for the duration of the time to take the sample, was determined through the use of the Fortran® computer program GASDEN. GASDEN was provided by The Gas Research Institute (GRI). GASDEN was capable of determining the density of CNG at all samples taken by simply inputting to GASDEN the temperature (^{o}F) and pressure (psi) during each collected sample. A copy of GASDEN is provided in Appendix B.

5 Experimental Apparatus

5.1 Overview of Experimental Setup

The time for the fuel fill process of a natural gas vehicle (NGV) must be comparable, in time, to the fuel fill process of a gasoline-fueled automobile in order to make an NGV a marketable or appealing automobile to drive or own. In order to achieve the desired time for the fill process of the (NGV) which, is a comparable time to a gasoline fill, a rapid charging system had to be developed. The system studied in this report achieves a desirable NGV fill time by utilizing a three-stage high pressure compression system (Norwalk® natural gas compressor). Tests were performed at the West Virginia University Physical Plant, which utilizes a Norwalk® natural gas compressor as well as tests performed at the BP® fueling station located in Westover, West Virginia in order to confirm that the flow meter for this project was calibrated correctly, and to acquire data from cascade system (section 5.6.3). A test rig needed to be built to better help in determining the characteristics of the natural gas during the 'fast fill' process. The test rig, which consists of a manifold with sensors (thermocouple, pressure transducer, and a flow meter with signal conditioner) and an NGV fuel storage cylinder with a thermo couple/thermo-well setup, measures the exact time (sec) for the fast fill to be executed, temperature (inside the manifold and in the approximate center of the storage cylinder in degrees F) , pressure (psi), and flow rate (SCFM) of the natural gas during the fuel fill process of an NGV. The test rig is an intrinsically safe piece of equipment. Intrinsically safe equipment is defined as: "equipment and wiring which is incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of specific hazardous atmospheric mixture in its most easily ignited concentration (ISA, [20]).” The data collected for this report was not collected while filling an actual NGV, but while filling an NGV Brunswick® composite natural gas vehicle storage cylinder (244 SCF or 2 gallon gasoline equivalent). Time, temperature, pressure, and flow rate are respectively determined through the use of sensors and a data acquisition system driven by a computer program. Through the use of the timer and sensors mentioned along with a data acquisition PC card and a computer driver code, characteristics of the natural gas during the ‘fast fill’ process could be determined.

Temperature, pressure, flow rate, and total volume of the ‘fast fill’ process were determined through the use of electronic sensors (thermo couple, pressure transducer, and flowmeter/signal conditioner) on a test manifold and sensors (thermo-well/thermo couple) in the Brunswick® cylinder with the use of an RTI-815™ data acquisition card manufactured by Analog Devices®. The RTI-815™ card in conjunction with a driver program that was written in QBasic™ code made it possible to decipher the output voltages of the sensors into the correct units or format that was needed to determine temperature, pressure, flow rate, and volume. The test rig sensors are summarized in Table 5.1-1.

Quantity	Description
2	Type-K thermocouples
2	(Cold junctions/thermocouple to analog connector) for the thermocouples
1	Pressure transducer
1	flow meter
1	signal conditioner (to convert pulse output from flow meter to 4-20 mA output)
1	thermo-well

Table 5.1-1 Test Rig Sensors

One thermocouple along with the thermo-well was used separately from the test manifold. The thermocouple and thermo-well were threaded into an NGV fuel storage cylinder o-ring plug. The 1-1/16" plug was drilled then tapped through its length with a ¾" NPT tap which is the thread type and diameter of the thermo-well setup. The plug, with the aforementioned thermocouple threaded into the thermo-well and the thermo-well threaded into it, was then inserted into the back (opposite end of the valve) end of the fuel storage cylinder to better determine the 'in-cylinder' temperature. The thermocouple and thermo-well combo have a penetration of approximately 12 inches into the storage tank, which can determine temperature characteristics in the vicinity the center of the tank. The second thermocouple, the pressure transducer, and the flow meter/signal conditioner were installed in line on a test manifold. The manifold consists of stainless steel (SS316) fittings and stainless steel (SS316) tubing along with the mentioned sensors. An illustration of this manifold setup is shown in Figure 5.1-1. The test manifold components are summarized in Table 5.1-2.

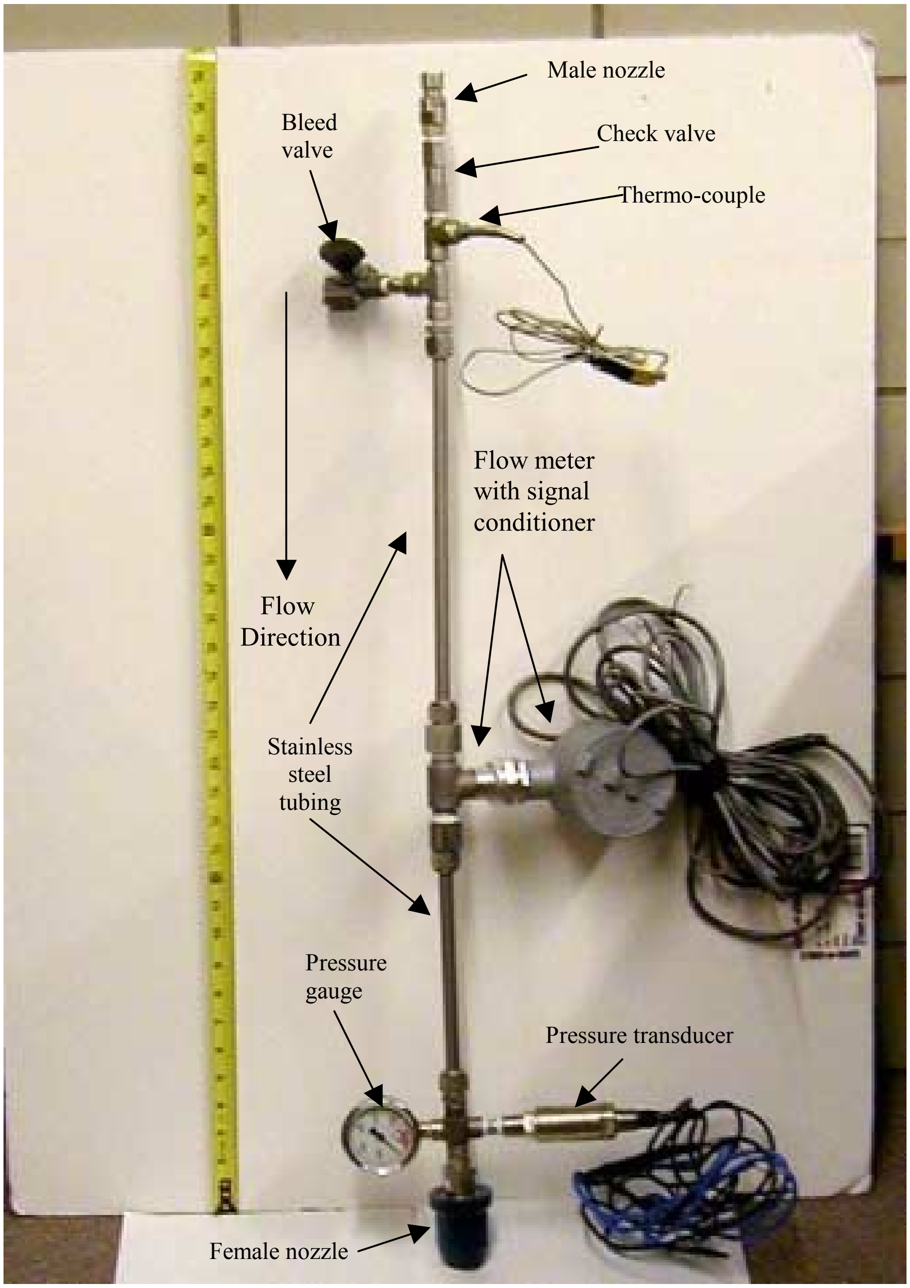


Figure 5.1-1 Test Manifold With Stainless Steel Components and Electronic Sensor.

Quantity	Description
1	Snap-Tite® male nozzle (NGVN2-P36); 9807
1	Snap-Tite® female nozzle (NGVC2-P30); type 2; class A; 9431
1	X-fitting
2	T-fitting
2	½" female NPT fitting to ½" tube compression fitting
2	¼" male NPT fitting to ½" tube compression fitting
1	Parker® SS316 check valve 4F-CAL-5-BN-SS
2	¼" male NPT fitting to ¼" male o-ring fitting
1	5000 psi dial gauge built by Automotive Research Technologies (ART)
2	¼" male to male NPT fitting
1	ball valve (manifold bleeder valve) Whitey® SS-33VF4
1	½" I.D. SS316 tube x appr. 7" long (.037" wall thickness)
1	½" I.D. SS316 tube x appr. 11.5" long (.037" wall thickness)

Table 5.1-2 Test Manifold Components

5.2 Data Acquisition

Time, temperature, pressure, and flow rate during the fill process and/or at end of the fast fill process is collected through the use of computerized data acquisition. The data acquisition setup is comprised of all pre-mentioned sensors (Table 5.1-1), an RTI-815 board manufactured by Analog Devices®, and software written in QBasic™ code. The RTI-815 board was installed in the ISA slot on the motherboard or main-board of the testing computer.

The QBasic™ code is responsible for determining the time it takes for the fill process to execute. Any temperature, pressure, and flow rate data is determined through the execution of the computer program in conjunction with the RTI-815 board. The RTI-815 board converts the direct current (dc) voltage output from the sensors into a number that the QBasic™ code can understand. Each sensor has a positive and negative wire that is connected to a differential channel on the terminal board for the RTI-815 board. Each sensor is connected to an individual differential channel. A differential channel is a channel in which the voltage difference between the positive and negative of that particular channel is measured which is the output voltage from a sensor. The number that is converted by the RTI-815 board is a number in the range of 0 to 4095 because it is a 12 bit analog voltage to digital number converter, which consists of 4096 bits because the number 0 (in the 0 – 4095 range) is included. The RTI-815 used for this test setup has a –5 volt to 5 volt operating range. The operating range is the voltage that a sensor must operate in to be able to be acknowledged by the RTI-815 board. In other words, a sensor must have an output signal somewhere in the –5 volt to 5 volt range in order for the RTI-815 board to acknowledge it, which all sensors in the test rig do. The QBasic™ computer code or driver program is illustrated in Appendix A.

The QBasic™ code is the driver program that makes it possible for the RTI-815 board to send data to the user in a usable form (digital numbers). The driver program also converts the digital number from the RTI-815 board to the proper units for temperature (^{o}F), pressure (psi), and flow rate (SCFM), and then saves the data to a data file where it can be used.

5.3 General Description of Test Manifold

The manifold setup, as mentioned earlier in this report, is comprised of stainless steel components (Table 5.1-2). The manifold has nozzles on each end. A bleeder valve is included to relieve pressure to allow the manifold to be disconnected. The manifold contains 3 electronic sensors: a type-K thermocouple, a pressure transducer and, a flow meter with a signal conditioner. A check valve was also installed for safety reasons. The components of the manifold are described in the following subsections.

5.3.1 Nozzles

The nozzles, one male and one female, are Snap-Tite® fittings which are 'quick connect' style fittings. Quick connect fittings can be defined as fittings that simply snap together without any tightening needed to obtain a sealed connection. The male nozzle is illustrated in Figure 5.1-1. The female nozzle on the other end of the manifold is illustrated in Figure 5.3-1. The blue female fitting is connected to the male fitting on the NGV, or the test cylinder for this particular project, which is also a Snap-Tite® quick connect fitting.

Figure 5.3-1 Female (Blue – 3000 psi) Snap-Tite® Quick Connect Nozzle.

The fill line from the compressor station dispensing unit, which has the same blue Snap-Tite® nozzle, is then connected to the male Snap-Tite® fitting of the manifold. All female Snap-Tite® nozzles are color-coded. The blue nozzle was chosen for this particular research project. Tests could be performed on 3000 psi and 3600 psi maximum allowable pressure NGV's or storage cylinders. The symbolization of the color of the nozzle is to indicate the maximum pressure output. For example, the blue nozzle can be used to fill a 3000 psi or a 3600 psi rated NGV. However, a yellow nozzle can fill only a 3600 psi rated NGV, and not an NGV with a lower maximum pressure rating. This system is made possible by the selection of the male fill nozzle located on the NGV, which indicates the maximum allowable pressure of the NGV. There are three separate color codes for these female nozzles: green, blue, or yellow which indicate a maximum compressor output pressure of 2400 psi, 3000 psi, or 3600 psi respectively. A better understanding can be accomplished by realizing that a green nozzle can fill any of the three rated pressure NGV's. In other words, the 2400 psi nozzle or green nozzle can fill the 2400psi, 3000 psi, or the 3600 psi NGV's, but the 3600 psi nozzle can not fill either of the two lower maximum allowable pressure NGV's. In the case that someone may forget these color codes, a safety precaution was made to assure that the mating of the two connectors can not be made unless the proper 'colored' female nozzle to male connecter nozzle is established. A description of allowable connections of the color coded nozzle to male connector nozzle is illustrated in Table 5.3-1. The Snap-Tite® fittings mentioned in this section were used for the testing compiled at the WVU physical plant.

female (supply) nozzle (color/pressure rating)	**male (receiving) nozzle (allowable connections; indicated by maximum allowable pressure of the NGV (male nozzle), to the female connector shown on the left)**
Green/2800 psi	2800psi, 3000psi or, 3600 psi
blue/3000 psi	3000 psi or 3600 psi
Yellow/3600 psi	3600 psi

Table 5.3-1 Allowable connections of the color-coded nozzle to male connector nozzle.

For the testing done at the BP® fueling station in Westover, WV, a male Parker Hannifin® fitting had to be incorporated into the test manifold. The Parker Hannifin® fitting was simply swapped with the male Snap-Tite® fitting on the test manifold. This exchange was done because the dispensing unit at the BP® station utilized a Parker Hannifin® female quick connect fitting rather than a Snap-Tite® fitting. The Parker Hannifin® fitting is an older style fitting, but does incorporate a check valve to compensate for pressure leaking back out of the system. The BP® NGV fueling station was set up to deliver a 3600 psi, opposed to the 3000 psi level from the WVU physical plant dispensing unit, fill level to the NGV's that it serviced. The Parker Hannifin® fitting is a 'one size fits all' construction. There is no color-coding or change in model to compensate for any changes in the supply pressure (2400, 3000, or 3600) from a dispenser. The Parker Hannifin® fitting is an inferior fitting in design and safety compared to the Snap-Tite® fitting, and is being phased out of the NGV market. The NGV industry is striving to make Snap-Tite® the universal style of fitting used at all NGV stations, which is good for safety and NGV fueling station infrastructure.

5.3.2 Bleeder Valve

The ‘bleeder valve’ needed to be incorporated into the manifold. The purpose of this bleeder valve is to alleviate pressure after the fast fill process has been completed. When dealing with high-pressure systems such as this, it is very important to include a bleeder valve into the system. The male and female nozzles mentioned earlier are virtually impossible to uncouple under any respectable pressure. Pressure remains in the manifold after the fill process has been completed due to the fact that the male and female connectors on each of the manifold’s ends also act as a check valve. A check valve is also in series with the male connector/check valve. Due to the fact that there are check valves on both sides of the manifold, the pressure in the manifold has no where to go except through the bleeder valve once it has been opened. If a bleeder valve were not included in the setup, it would be impossible to disconnect the manifold from the NGV or the supply line from the male end of the manifold once a fill has been completed. All compressor stations have a similar relief system in place, which makes it possible to disconnect the supply line from the male connector located on the NGV or in this case the test manifold.

5.3.3 Check Valve

The manifold is equipped with a check valve. The check valve was placed directly downstream from the male Snap-Tite® or Parker Hannifin® fitting as illustrated in Figure 5.1-1. The check valve was used as a safety device in the case that something would ever go wrong with the male quick connect fitting (mainly the Parker Hannifin® fitting). The check valve used was a Parker® (4Z-C4L-5-BN-SS) check valve. Pressure drops across the cylinder are described in Figure 5.3-2. The graph illustrated in Figure 5.3-2 was constructed from information supplied by Parker®, and noted by the company that no testing was performed to verify the information therefore calculations alone are an approximation.

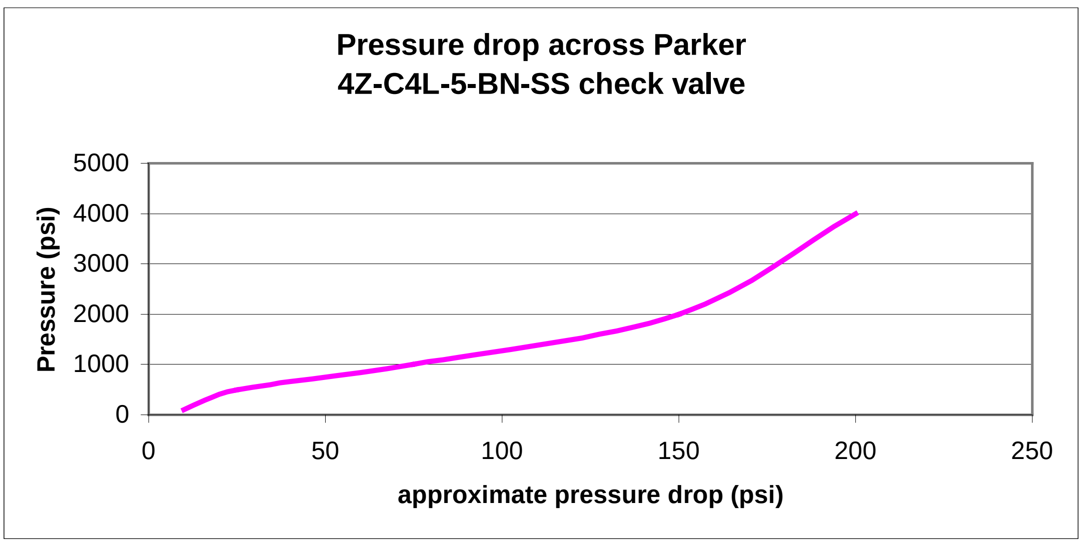


Figure 5.3-2 Pressure drop across Parker® check valve

5.3.4 Thermocouple on Test Manifold

A type-K thermocouple was chosen to measure temperature in the manifold during the fill process. Knowing the temperature and pressure (with the help of a pressure transducer) in the manifold made it possible to determine the density of the natural gas in the manifold. The flowmeter was also dependent on the temperature in the manifold to convert from ACFM (Actual Cubic Feet per Minute) to SCFM (Standard Cubic Feet). The thermocouple chosen utilizes an ungrounded junction. An ungrounded junction is recommended for measurements in corrosive environments where it is desirable to have the thermocouple electronically isolated from and shielded by the sheath. A high-pressure thermocouple plug sensor with a ¼" NPT fitting was chosen which easily threads into the test manifold and can operate in high-pressure conditions. The thermocouple sensor chosen is designed for high-pressure applications, and is manufactured by Omega® Engineering. An electronic cold junction also needed to be purchased from Omega®. The purpose of the cold junction or 'reference' junction is to mimic a physical cold junction of the thermocouple set up. The cold junction (Omega® SMCJ-K) has an output of .001 volt per degree temperature change, sensed by the thermocouple, which simplifies the software coding process. The cold junction can give an output of 1 mV/degree change, Fahrenheit or Celsius, based upon which unit the user chooses. An illustration of the cold junction and thermocouple setup is shown in Figure 5.3-3.

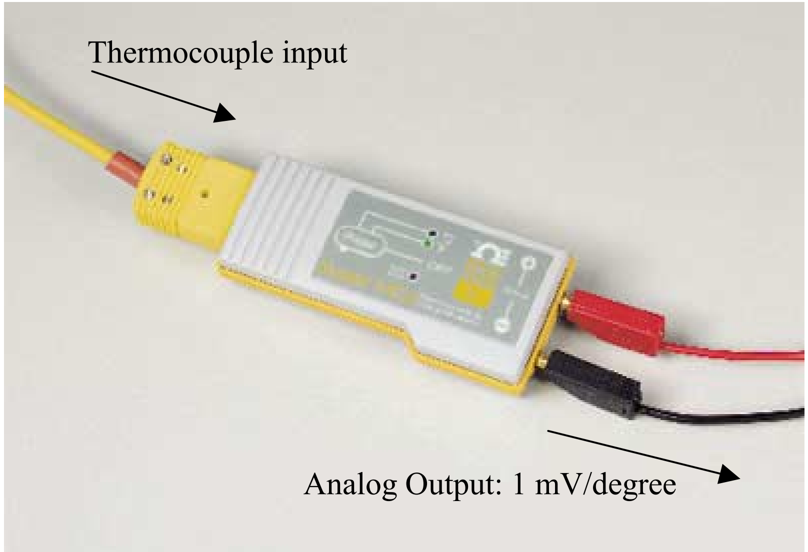


Figure 5.3-3 Illustration of Electronic Cold Junction.

5.3.5 Pressure Transducer

A PX41 series heavy-duty industrial pressure transmitter was purchased from Omega® to meter the pressure of the natural gas during the fast fill process. The PX41 transducer has a 0–5000 psi operating range with a 4-20 milliamp current loop output. A 250 Ω resistor (+/- .25 Ω) needed to be used to convert the 4-20 mA sensor output to a 1-5 Volt sensor output through Ohms' Law. The accuracy in the voltage output of the sensor due to the tolerance of the resistor used would be 1 +/- .001 Volts – 5 +/ .001 volts. The resistor was placed across the positive and negative of the selected differential channel on the terminal board of the RTI-815 data acquisition card. The 0-5000 psi transducer range can give an accurate reading with good resolution (+/- 3.05 +/- .001 psi). The (+/-) 3.05 psi is the smallest pressure change that can be acknowledged by the RTI-

815 data acquisition card and software. The PX41 series transducer is a standard FM/CSA (Factory Mutual/Canadian Standards Administration) intrinsically safe piece of equipment. The optional FM approved for hazardous locations feature was also selected as a safety precaution to avoid any explosions due to any possible gas leaks in the test rig or immediate area. The operating environment is described as a hazardous (classified) location in Accordance with Article 500, National Electrical Code – 1990. According to the electrical code, the operating environment for the test rig can be considered a Class 1– Division 2 – Group D environment or location. The code for electrical equipment operating in the presence or possibility of the presence of flammable gasses or vapors is illustrated in Appendix C. The pressure transducer is illustrated in Figure 5.3-4. A schematic of the pressure transducer is displayed in Figure 5.3-5.

Figure 5.3-4 Omega® PX41 Pressure Transducer

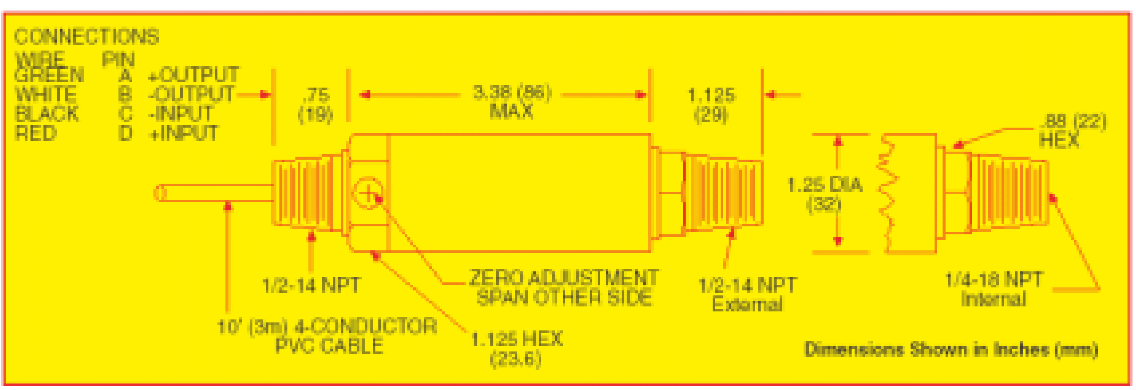


Figure 5.3-5 Schematic of Pressure Transducer

5.3.6 Flow Meter and Signal Conditioner

The FTB-933 model ball bearing gas turbine flowmeter was purchased from Omega® to measure natural gas flow in the manifold. The FTB-933 flowmeter is NIST certified, and is capable of +/-1% reading accuracy. A signal conditioner (FLSC-60), which is integrally mounted to the flow meter, was also purchased from Omega®. The flowmeter / signal conditioner combination is FM approved and CSA certified, Class I groups, B, C, D, Class II E, F, G piece of equipment which makes it intrinsically safe. The FLSC-60 signal conditioner converts the pulse output created by the FTB-933 flow meter to a 4-20 milliamp output, which can be easily monitored by the RTI-815 and software. As in the case of the pressure transducer mentioned early, the 4-20 mA output from the FLSC-60 had to be converted to a 1-5 volt dc output through the use of a 250Ω resistor with a tolerance of .25Ω placed across the selected differential channel on the RTI-815 terminal board. Due to the low density of natural gas, the FTB-933 needed to be fit with custom ball bearings and a custom rotor in order to operate properly in a natural gas environment. The FTB-933 has male ½" NPT end fittings, which provided means for easy connection. It would have been more practical to use a flow meter with ¼" NPT fittings since the rest of the test manifold is constructed of ¼" fittings, but there were no available flow meters that size in an affordable price range that could support the high pressures present in the test manifold. To incorporate the ½" fittings, the manifold had to be modified to accommodate FTB-933 flow meter. The FTB-933 could not simply be placed inline with the manifold. It had to have ½" tubing placed upstream and downstream of the meter. The ½" tubing was installed to compensate for any turbulence created by the sudden increase in flow area which could cause false flowmeter readings or ultimately cause failure of the flowmeter. The ½" tubing had to be at least 5 tubing diameters in length (2.5 inches) down stream from the flowmeter, and 10 tubing diameters in length (5 inches) upstream to the flowmeter as indicated by Omega®. The manifold possesses lengths of tubing that exceeds the minimum requirements upstream and downstream by incorporating upstream and downstream lengths of 11¼" and 7" respectively. The extra length of tubing acts as a safety factor to assure that the flowmeter has the proper operating environment in which to provide correct flow measurements. The stainless steel tubing can be viewed in Figure 5.1-1 shown previously in this report. An illustration of the FTB-933 flowmeter and the FLSC-60 signal conditioner is illustrated in Figure 5.3-6. A description on how to disassemble and reassemble as well a detailed schematic of the flowmeter and it's components is illustrated in Appendix D. An illustration of upstream and downstream mounting suggestions for the flowmeter is also provided in Appendix D.

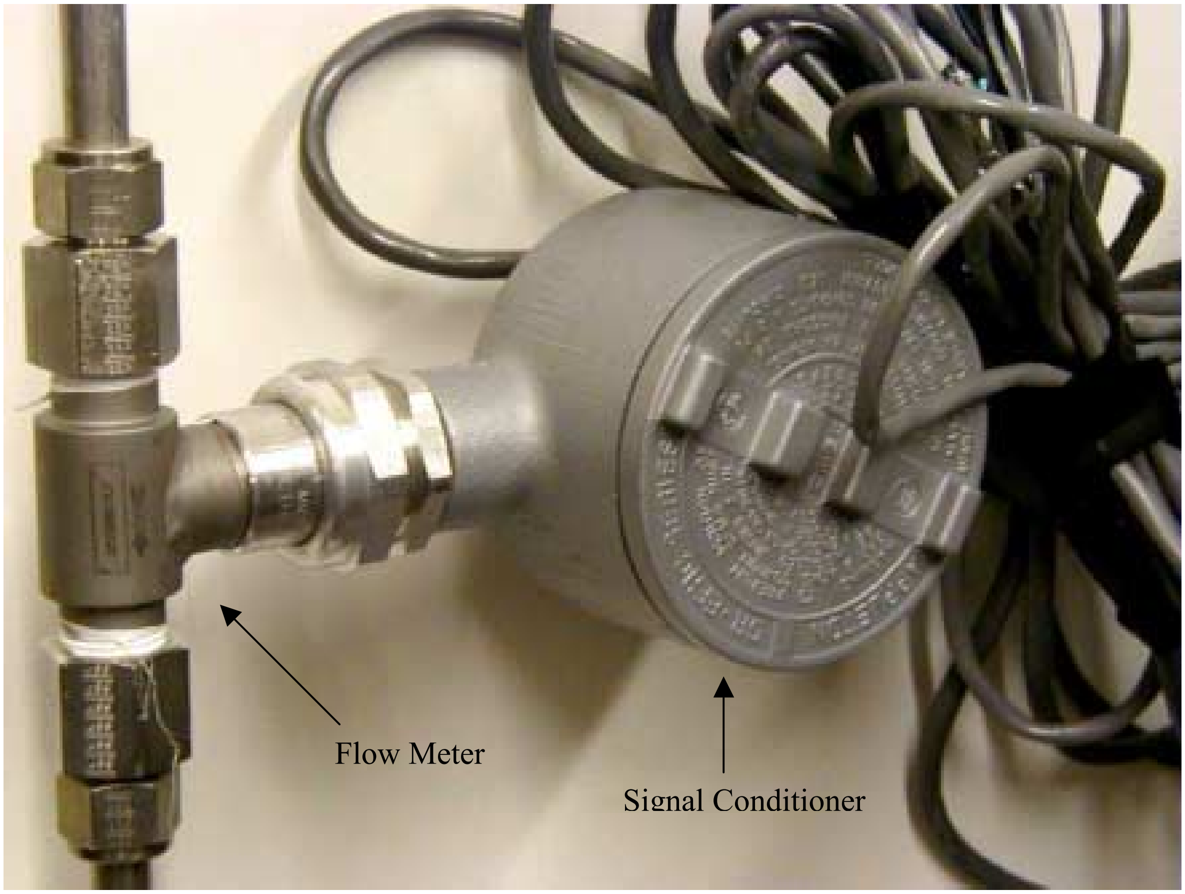


Figure 5.3-6 Omega® FTB-933 Flow Meter and Omega® FLSC-60 Signal Conditioner.

The FTB-933 flow meter is a turbine flowmeter. The fluid flowing through the turbine flowmeter engages a vaned rotor, causing it to rotate at an angular velocity that is directly proportional to the flow rate. As the turbine rotates, an AC voltage is induced in a magnetic pickup coil mounted outside the fluid process. As each turbine blade passes the base of the pickup coil, the magnetic flux density is affected, inducing a voltage pulse. Each pulse represents a distinct volume of fluid that has been displaced through two adjacent rotor blades. The pulse rate generated is thus a very accurate measure of flowrate, and the total number of pulses an equally accurate measure of displaced volume (Omega Engineering, [21]).

All transducers benefit from the use of integral signal conditioning. When a signal conditioner is mounted in close proximity to the sensor, the possibility of signal interference and distortion is significantly reduced. The conditioner takes the low-level sensor output and conditions, amplifies, and transmits a high-level signal which is less likely to be affected by ambient conditions, thereby preserving system accuracy.

The FTB-933 is a volumetric flowmeter. The flowmeter was designed to measure actual cubic feet or actual volume passing trough the meter. The flow meter used in this project was set up to measure actual cubic feet per minute flow rate. To convert from actual cubic feet per minute (ACFM) to standard cubic feet per minute (SCFM) a conversion equation has to be incorporated. The equation used for the conversion is shown below, Equation 5.3-1.

Equation 5.3-1 $$\mathbf{ACFM = SCFM * 14.7 / Pa * Ta / 530}$$

Where ACFM = actual cubic feet per minute measured gas flow, SCFM = standard cubic feet per minute gas flow, Pa = operating pressure in (PSIA) = PSIG + 14.7, Ta = temperature in degrees Rankine = ^{o}F + 460 (Omega Engineering, [22]). Equation 5.3-1 is incorporated into the computer program to convert the measured gas flow from ACFM to SCFM. A copy of the computer program is available in Appendix A.

CNG dispensers utilize Gasoline Gallon Equivilant (GGE) units to measure flow and volume. CNG flow is designated as Gasoline Gallon Equivalent per Minute flow (GGE/min) and conversely CNG volume distributed to an NGV is represented by GGE.

The CNG industry uses the conversion of 1 gallon of gasoline = 5.66 lbm which a standard conversion.

A conversion process needed to executed to convert the ACFM readout from the flow meter to GGE/min. To complete the process, a conversion process had to be used. The first step in transforming ACFM to GGE/min was to determine the density of the CNG near the flowmeter while the meter was acquiring data. To determine the density of the CNG at desired times the Fortran® program GASDEN (section 4.3) needed to be executed. The GASDEN program was provided by The Gas Research Institute (GRI). GASDEN computed the density of CNG at any temperature and pressure that was inputted to it. For example, for every flow rate sample there was a temperature and pressure reading that took place at approximately the same time. The temperature and pressure readings were supplied via the manifold thermocouple and the pressure transducer mentioned previously. Upon determining the density of CNG in the flowmeter, an equation which converted volumetric flow to mass flow was executed. The conversion for volumetric flow to mass flow is described in Equation 5.3-2.

Equation 5.3-2 $$\mathbf{m = \rho * Q}$$

Where, m = mass flow rate (lbm/min), ρ = density of CNG (lb/ft^3), and Q = volumetric flow rate (ACFM). When Equation 5.3-2 was executed the units of measure could be displayed in lb_m/min. Knowing that the mass of 1 gasoline gallon equivalent (GGE) is equal to 5.66 lb_m natural gas it was then possible to convert the flow to GGE/min through simply multiplying the results of Equation 5.3-2 times: 1GGE / 5.66 lbm. GGE/min is a unit common to the CNG industry more so than other flow measurement units.

5.4 Test Cylinder

Due to the unavailability of an NGV on a regular basis for aid in testing, an alternative resource needed to be used. To compensate for the lack of a readily available NGV, a test cylinder was used. The test cylinder is a Brunswick® natural gas vehicle CNG storage cylinder. Brunswick® cylinders are now a part of Lincoln Composites®, which produces the Tuff Shell ™ all composite line of NGV cylinders, identical to the previously mentioned Brunswick®. Some useful information about the test cylinder is illustrated in Table 5.4-1. All information shown in Table 5.4-1 pertains to the 3600 psi rated cylinder. The test cylinder has a natural gas capacity of 244 SCF, which is equivalent to 2 gallons of gasoline. Natural gas capacity is based on a tank at service pressure filled with gas at a specific gravity of 0.60 and a temperature of 70^{o}F. All information in Table 5.4-1 is based on 124 SCF per equivalent gallon gasoline (EGG), and 139 SCF per equivalent gallon diesel (EGD) (Advanced Technical Products Inc., [23]).

Size ***(OD x Length)***		***Weight***		***Water Volume***		***Gas*** ***Capacity***	***Gasoline*** ***Equivilant***		***Diesel*** ***Equivilant***	
In	mm	Lbs	Kg	Cu. In	Liters	SCF	Gallons	Liters	Gallons	Liters
9.2 x 35	234 x 889	37	16.6	1429	23.4	244	2.0	7.5	1.8	6.5

Table 5.4-1 Information on the Brunswick® cylinder used for testing

The test cylinder was placed in a wooden case built specially to house the cylinder. The case has a hinged arm on its top side which can stay in the horizontal position which makes for easy transportation or it can be 'swung' into the vertical position which acts as a support for the test manifold during testing. An illustration of the test cylinder in the wooden crate with the test manifold attached is shown in Figure 5.4-1. The test cylinder has a thermocouple and thermo-well setup which measures in cylinder temperature during the fill process. The thermocouple/thermo-well setup is discussed in the following subsection.

Figure 5.4-1 Illustration of the Test Cylinder in the Wooden Case with the Test Manifold Attached.

5.4.1 Thermocouple/Thermo-Well Setup

An effective method of measuring the in cylinder temperature during the fast fill process was necessary. The thermocouple placed on the test manifold does not properly depict the temperature in the cylinder. The two areas in which the temperature during the process was recorded was: (1) the test manifold and (2) the inside of the cylinder. Through the use of a thermo-well/thermocouple setup placed in the end of the test cylinder, the temperature near the center of the cylinder could be determined. A thermo-well had to be used to compensate for the high pressure present inside the test cylinder. Safety was the deciding factor in choosing a thermo-well/thermocouple setup rather than just an unsheathed thermocouple. Upon the decision to use a thermo-well/thermocouple setup, delays in the response time had to be accounted for. The thermo-well, with a thermocouple, penetrates into the cylinder approximately 15 inches, which can give a representation of what the near center inner cylinder temperature is during the fill process. An illustration of the thermo-well/thermocouple setup is illustrated in Figure 5.4-2. Where U = 13-1/2” (which creates an x/L ratio of .39 into the test cylinder), Q = ¾”, P = ¾”, and A = 15”, and all dimensions shown on the schematic are in inches. The thermo-well is comprised of stainless steel (SS316). From the schematic, A is the stem length of the thermocouple inserted into the pictured thermo-well.

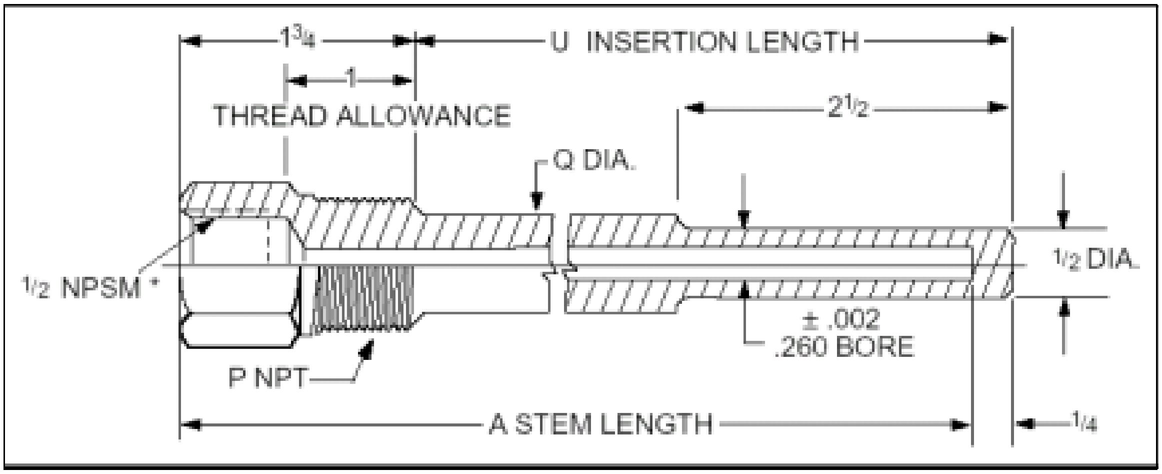


Figure 5.4-2 Schematic of Thermo-well/Thermocouple Setup.

The thermocouple coated with Omega® Omegatherm™ (thermally conductive silicon paste) was inserted into the thermo-well. Omegatherm™ provides an excellent means of conducting heat and expanding the heat-path area from a surface to a temperature measurement sensor, thus increasing the speed of response and improving accuracy (Omega Engineering, [24]). Some typical properties the thermally conductive silicon paste as listed by the manufacturer are illustrated in Table 5.4-2. The thermocouple output had to be run through an electronic cold junction before it was connected to its differential channel, which was the same device described in section 5.3.4 which was illustrated in Figure 5.3-3.

Color	Off-white
Temperature Range of Use	-40 to 392 ^oF
Consistency	Thick, smooth paste
Volume resistivity	10^{14} ohm-cm
Dielectric Strength	500 volts / mil (19.7 kv/mm)
Thermal Conductivity	16 (Btu)(in) / (hr)(ft^2)(^{o}F)
Specific Gravity	2.53 g / cc
Weight Loss	0.2 % (24 hours / 100^{o}C)
Shelf Life	1 year (Storage at 35^{o}F or below will approximately double shelf life).
Solvents	Alcohol or MEK or Xylene solvents

Table 5.4-2 Typical properties of Omegatherm® Thermally Conductive Silicone Paste

The thermocouple/thermo-well setup experiences a first-order step response. The first order step response is graphically explained in Figure 5.4-3 (Doebelin, [25]). The use of a thermo-well has a definite effect on the 'response' of the temperature measurement. The thermal measuring system was considered to be in equilibrium with the ambient at the start of the test.

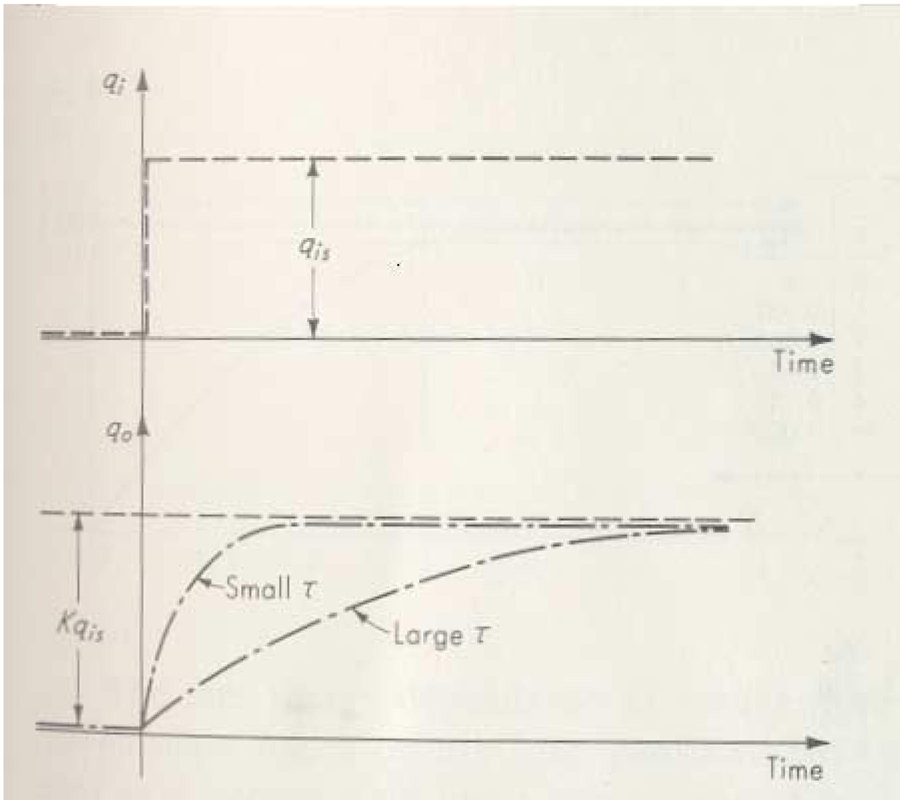


Figure 5.4-3 Graphical Representation of First Order Step Response.

Since the system is assumed to be in the equilibrium with the thermal surroundings at the start of a test, then $q_i = q_o = 0$, and the quantity of the input will increase by the amount q_{is}. K is the static sensitivity of the system, which is linear. The time constant of the system is denoted by τ. The illustration displays the curve of the first order system, and the affect of increasing or decreasing the time constant of the equipment in use when attempting to achieve equilibrium with the test environment. For a measurement to be as accurate as possible, the lower the time constant the better response time will be present. The time constant for the thermo-well / thermocouple setup is in the order of 1 ½ minutes, which is not an exceptionally quick responding instrument. The system is not a dynamic system in the sense that the temperature does not fluctuate up and down sporadically in large orders of magnitude, rather a constant increase due to heat of compression taking place in the test cylinder which allows the thermo-well / thermocouple setup to be a sufficient means of measuring temperature rise in the test cylinder.

5.4.2 Test Cylinder Valve

The Brunswick® test cylinder contains an interchangeable valve to control flow to or from the cylinder. The Brunswick® cylinder is nothing more than a shell with one 1.0625" tapped straight thread hole on each of it's ends. On one end of the cylinder is the aforementioned thermo-well / thermocouple setup, and on the other is a valve. The valve is manufactured by Superior Valve Company, and is designated as a 'high pressure horizontal valve with vent type safety'. Superior Valve Company was bought out, and is now a part of GFI Controls (Gaseous Fuels Incorporated). GFI was able to provide a schematic of the valve (Figure 5.4-5) as well as the C_v rating (0.83) fully opened, the operating temperature limits (-40^{o}F to 180^{o}F), and the maximum service pressure (3600 psi). The C_v rating or flow coefficient is defined as 'the flow in gallons per minute of water at 60^{o}F with a pressure drop of one psi (Lyons, Askland, [26])."

Knowing the flow coefficient it was then possible to determine the pressure drop (ΔP) across the valve. The pressure drop can be determined using the equation for flow of gases through a valve. The pressure drop equation is illustrated in Equation 5.4-1.

Equation 5.4-1 $\Delta P = ((q_m')^2 * S * T_1) / (P_1' * 22.67^2 * C_v^2)$

Equation 5.4-1 was provided by the "Lyons' Encyclopedia of Valves". Where q_m' = flow rate (SCFM), $S = \rho_{nat.\ gas} / \rho_{water}$ = specific gravity relative to water (unitless), T_1 = absolute temperature (^oR), P_1' = absolute pressure (psi), and C_v = flow coefficient (unitless). The pressure drop across the valve throughout the fast fill process is illustrated graphically in the results section of this report (Chapter 6).

The Superior valve is an angle valve with two 90^o angles between the inlet and outlet of the valve. "Angle valves are single-seated valves with special body configurations to suit specific piping or flow requirements. A discharge into the outlet pipe (with flow direction tending to close the plug) prevents erosion of the inside of the valve housing. A digital image of the valve is illustrated in Figure 5.4-4.

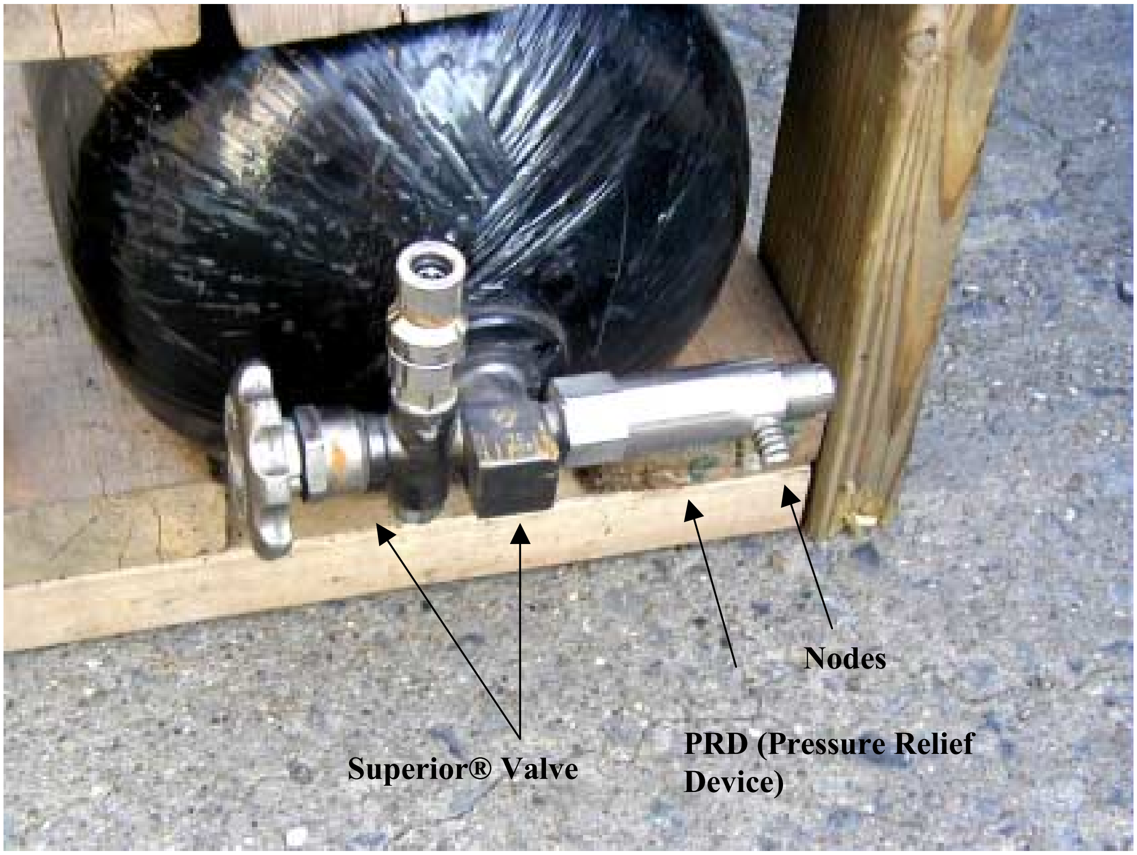


Figure 5.4-4 Illustration of Superior® Valve with PRD and male Snap-Tite® Fitting.

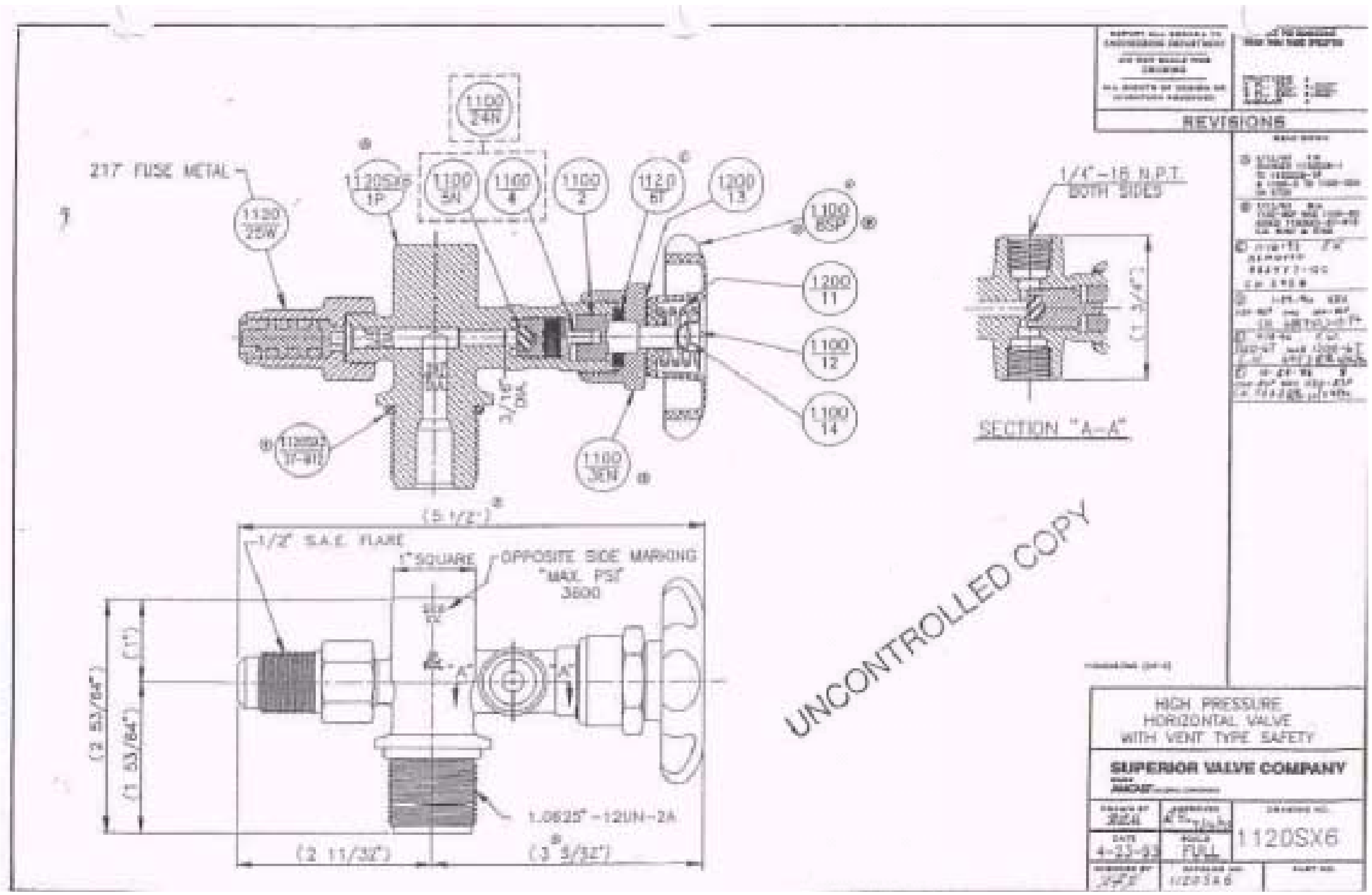


Figure 5.4-5 Schematic of Superior® Valve.

5.4.3 Relief Valve Mounted on the Flow Control Valve

Notice in Figure 5.4-4 that there is a PRD (Pressure Relief Device) mounted on the Superior® flow control valve. This device is in place for safety concerns. If the pressure in the cylinder and/or valve becomes too high, the PRD will be utilized to alleviate pressure from the system. The PRD has nodes on its outer tip comprised of lead. If the nodes are exposed to extreme heat (melting point of lead) or pressure the nodes will break, thus alleviating pressure from the cylinder. The PRD is manufactured by Mirada Controls®.

5.5 Compressor

The WVU Physical Plant utilizes a Norwalk® (NQ-SV3 "Charger") natural gas compressor or charger to supply all of the physical plant fleet vehicles with CNG. Natural gas is supplied to the compressor from Dominion Transmission Incorporated® through the use of an underground supply line. The charger is a three-stage, vertically mounted high-pressure compressor. The three-stage compression process is shown in Table 5.5-1. The natural gas is compressed in the first stage to a pressure of 140-195 psig then transferred to the second stage of compression where it is compressed to 700-900 psig then transferred to the third stage of compression where the gas is finally compressed to 3600 psig. A vertical cross section of the Norwalk® compressor is illustrated in Figure 5.5-1.

Item	***Normal Operating Position or Indication and Function***
1st stage Pressure gauge range (0-350 psig)	140-195 psig –indicates discharge pressure from 1st stage cylinder assembly
2nd stage Pressure gauge range (0-1500 psig)	700-900 psig –indicates discharge pressure from 2nd stage cylinder assembly
3rd stage Pressure gauge range (0-5000 psig)	3600 psig –indicates discharge pressure from 3rd stage cylinder assembly

Table 5.5-1 Operating Controls and Indicators For Norwalk Compressor.

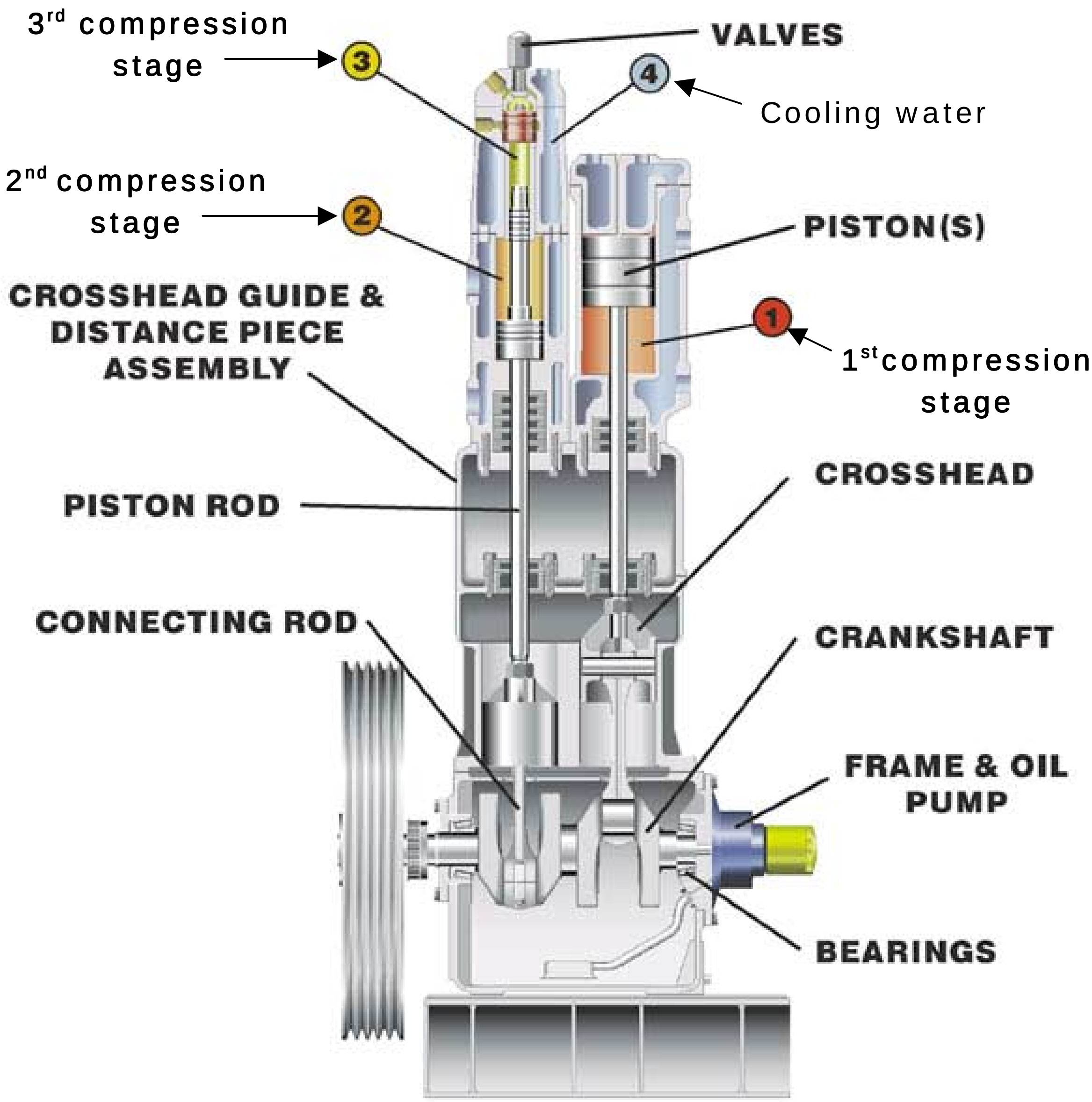


Figure 5.5-1 Vertical cross section of Norwalk Natural Gas Charger (Compressor).

5.6 CNG Storage Bank

Most NGV refueling stations use a storage bank of some sort to store CNG from a natural gas compressor before it is dispensed to the NGV. Some stations, however, do use a direct fill from a compressor method. For this project only storage bank type NGV refueling stations were considered. Two methods of storage are used in NGV fueling stations: (1) the cascade storage system and a (2) single control volume system. The cascade system is the most widely used system used today to 'fast fill' vehicles with CNG, which is a three-bank cascade storage system. The single control volume system is also a system used to store CNG before it is dispensed to an NGV. The single control volume system, which normally incorporates a 'dome load' valve is a system not as efficient for refueling NGV's as the cascade system. Both systems are described in the following paragraphs.

5.6.1 Single Control Volume System

The Norwalk® compressor does not directly fill the vehicles, rather it fills a series of upright cylinders (DOT 3600AA). This method is used to speed up the fill process. By filling these cylinders to a high pressure, greater than the required pressure for the NGV being serviced, fill time is greatly reduced by not directly filling NGV's via a natural gas compressor. The series of upright cylinders acts as one large control volume. This is not new technology. The latest technology in CNG filling stations uses a 'cascade system'. The CNG control volume at the physical plant is comprised of 2 "baskets" of tanks, each basket contains 24 upright cylinders or tanks. The cylinders are all connected in series (48 all together). The cylinders were manufactured by Norris®. An illustration of the control volume or storage bank and a dome load valve, which will be discussed in the following sub-section is illustrated in Figure 5.6-1.

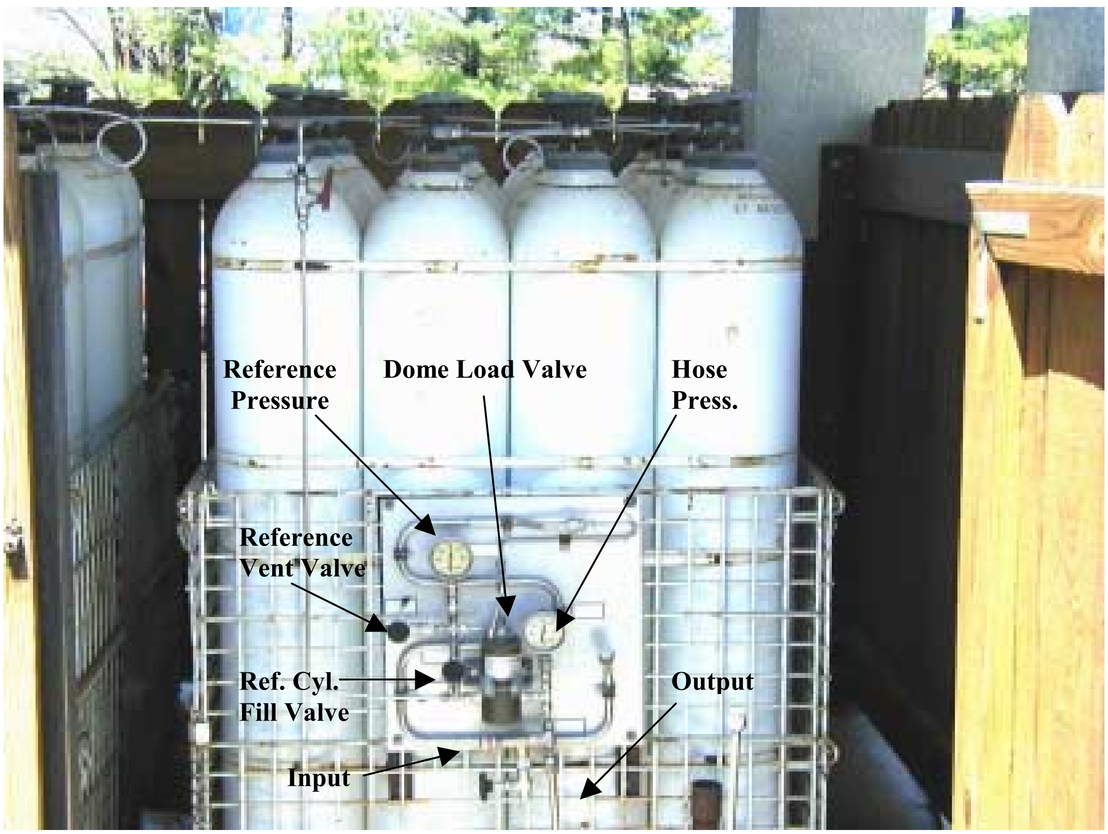


Figure 5.6-1 CNG single control volume storage bank (basket) comprised of DOT containers for NGV refueling.

The cylinders are DOT cylinders and have a rating of 3600 psi, which means the CNG contained in them should not exceed 3600 psi. This 48 cylinder system acts as a single control volume. The storage system is set up to deliver a 3000 psi charge to the NGV's. The 3000 psi charge is determined through the use of the storage system and the 'dome load' valve described in the following section.

5.6.2 Dome Load Valve

The flow to the NGV from the single control volume storage cylinders is controlled by a 'dome load' system.   The particular dome load assembly utilized by the physical plant is a mechanical unit. A dome load is simply a mechanical or electronic valve that compensates for ambient temperature change while filling an NGV. A dome load valve is used to provide the proper vehicle fill level without over-pressurizing an NGV. The dome load valve is usually cased in a dispenser unit if it utilized by a public CNG service station. CNG dispensers will be discussed in greater detail in the following section. The dome load valve is used to determine when to stop the NGV fill process.

The purpose of a dome load valve is to supply CNG from the storage cylinders to the NGV while continually compensating for ambient temperature changes during the fill process. The dome load valve is a hydraulic slide valve with three factors that it considers to determine a full fill. The three factors are shown in Table 5.6-1.

The Three factors the 'Dome Load' valve at the WVU physical plant CNG fill station uses to determine fill level on NGV's	
1	Pressure in the storage tank(s).
2	Output pressure to the dispenser.
3	A reference tube that was calibrated for 3000 psi and 70^{o}F.

Table 5.6-1 Factors the 'Dome Load' valve uses to determine a full fill on an NGV.

The third factor mentioned in Table 5.6-1, the reference tube is sealed on it's end and the trapped gas expands or contracts based on ambient temperature. The dome load valve and it's reference factors are illustrated in Figure 5.6-1.

One particular pit fall of a dome load valve is that it does not take the temperature rise inside the tank(s) of the NGV into consideration. A temperature rise occurs inside the tank due to heat of compression, which will be displayed in the results section of this report. This causes the dome load valve to under-fill the vehicle by 6% to 20% under normal conditions (Yeremian, [27]). Dome load valves are now generally considered inappropriate for obtaining complete vehicle fills (Neilson, et al, [28]).

Dome load valves are being phased out of the CNG industry. As mentioned, they are not very efficient in terms of providing a full fill to the NGV. NGV station technology has moved to the cascade system with the Electronic Switching Device (ESD) / Priority Panel. The cascade system is capable of providing a closer to NGV fuel storage capacity fill to the vehicle.

The compressor at the physical plant never filled the storage bank to a high enough pressure to deliver a 3600 psi fill to the test cylinder used in this project or to any of the physical plant fleet NGV's. The CNG filling station was set up to fill vehicles to approximately the 3000 psi level (plus or minus 200 psi), due to the fact that most NGV's on the physical plant fleet were equipped to operate at a fuel storage pressure of 3000 psi based upon their fuel cylinder specifications. The Norwalk® compressor did not need to compress the natural gas to the storage bank as high as it would if it were used to fill 3600 psi rated NGV's exclusively.

5.6.3 Cascade Storage Systems

Cascade systems are the most commonly used system to fast fill vehicles with CNG. The cascade system is more efficient than the single control volume system. The system at the BP® service station in Westover, WV utilizes a cascade system. The cascade system uses a three-bank storage system designated by a low, medium, and high storage bank. The system at the fueling station in Westover utilizes DOT cylinders arranged in 'baskets' similar to the DOT containers and baskets mentioned in the single control volume explanation for the WVU physical plant. The three-stage bank can also be assembled from ASME containers, which are much larger in size, but can greatly reduce the amount of tubing and fittings that are needed to connect the DOT container 'baskets' together. DOT containers have to be taken out of service every 5 years and hydrotested, whereas ASME containers are certified for life. The ASME CNG containers can also be arranged in a 'stacked' position, which can maximize space at a refueling station. An illustration of a cascade system utilizing ASME containers stacked on top of each other is shown in Figure 5.6-2.

Figure 5.6-2 Illustration of ASME (high, medium, low) storage bank vessels stacked on top of each other to maximize NGV compressor station ground space.

The baskets of DOT containers used at the BP® compressor station are arranged differently than the system used at the WVU physical plant. The system at the BP® fueling station is a three basket assembly arranged in a three stage storage bank order (low, medium, and high). The three-stage assembly is configured to contain approximately 33% of the total storage volume in each particular stage. The supply of CNG from a cascade system is controlled by a sequential (ESD) and priority valve panel.

5.6.4 An example of how the Cascade System Utilizes a Three Stage Storage Bank to Provide a More Efficient System than the Single Control Volume Storage Supply

An article published by RP publishing written by Ralph O. Dowling of C.P. Industries is summarized in this section to better describe the cascade system (Dowling, [29]). The cascade system as mentioned earlier is a more efficient system than the single control volume storage supply. A brief description of how the cascade operates will be described in the following paragraphs. An understanding of the effects of compression on natural gas is the first step in understanding the cascade system. Table 5.6-2 illustrates how natural gas is affected when compressed into 1 ft^3 water volume.

Gage pressure psi	scf/ ft3 water volume	Gage pressure psi	scf/ ft3 water volume	Gage pressure psi	scf/ ft3 water volume	Gage pressure psi	scf/ ft3 water volume	Gage pressure psi	scf/ ft3 water volume	Gage pressure psi	scf/ ft3 water volume	Gage pressure psi	scf/ ft3 water volume	Gage pressure psi	scf/ ft3 water volume
0	1	700	54.04	1400	117.39	2100	185.67	2800	244.92	3500	290.24	4200	325.9	4900	353.14
25	2.71	725	56.24	1425	119.76	2125	187.87	2825	246.78	3525	291.95	4225	327.09	4925	353.82
50	4.45	750	58.47	1450	122.29	2150	190.06	2850	248.64	3550	293.3	4250	327.9	4950	354.86
75	6.18	775	60.58	1475	124.68	2175	192.26	2875	250.49	3575	294.65	4275	328.71	4975	355.9
100	7.92	800	62.64	1500	127.24	2200	194.45	2900	252.33	3600	296.34	4300	329.88	5000	356.93
125	9.74	825	64.86	1525	129.66	2225	196.65	2925	254.17	3625	297.32	4325	331.05	5025	358.71
150	11.55	850	67.01	1550	132.26	2250	198.84	2950	256.01	3650	298.29	4350	332.21	5050	358.9
175	13.33	875	69.27	1575	134.71	2275	201.04	2975	257.84	3675	299.6	4375	333.37	5075	360.38
200	15.15	900	71.54	1600	137.34	2300	203.23	3000	259.67	3700	300.92	4400	334.52	5100	361.78
225	16.95	925	73.67	1625	139.82	2325	205.69	3025	261.16	3725	302.22	4425	335.3	5125	362.04
250	18.76	950	75.8	1650	142.13	2350	207.89	3050	262.64	3750	303.52	4450	336.4	5150	362.3
275	20.58	975	77.86	1675	144.62	2375	210.36	3075	264.12	3775	304.81	4475	337.2	5175	363.31
300	22.49	1000	80.01	1700	147.13	2400	213.39	3100	265.59	3800	306.46	4500	338.33	5200	364.31
325	24.43	1025	82.26	1725	149.47	2425	214.76	3125	266.72	3825	308.11	4525	339.46	5225	365.3
350	26.34	1050	84.54	1750	151.81	2450	216.96	3150	267.84	3850	309.38	4550	340.58	5250	365.92
375	28.18	1075	86.83	1775	153.96	2475	219.16	3175	270.63	3875	310.65	4575	341.69	5275	366.17
400	30.02	1100	89.24	1800	156.31	2500	221.36	3200	271.73	3900	311.92	4600	342.43	5300	367.15
425	32	1125	91.56	1825	158.86	2525	223.28	3225	273.43	3925	313.18	4625	343.16	5325	367.76
450	33.93	1150	93.79	1850	161.43	2550	225.47	3250	275.14	3950	314.06	4650	343.89	5350	368.73
475	35.83	1175	96.14	1875	164.01	2575	227.38	3275	277.38	3975	315.31	4675	344.99	5375	369.33
500	37.82	1200	98.4	1900	166.61	2600	229.57	3300	278.46	4000	316.55	4700	345.71	5400	370.3
525	39.83	1225	100.9	1925	169	2625	231.47	3325	280.21	4025	318.15	4725	347.16	5425	370.89
550	41.86	1250	103.19	1950	171.26	2650	233.06	3350	281.61	4050	319.38	4750	348.62	5450	371.85
575	43.9	1275	105.48	1975	173.58	2675	234.94	3375	283.36	4075	320.61	4775	349.36	5475	372.43
600	45.96	1300	107.78	2000	175.76	2700	236.82	3400	284.75	4100	321.82	4800	350.39	5500	373.38
625	47.94	1325	110.23	2025	178.17	2725	239.01	3425	286.13	4125	323.04	4825	351.09	5525	373.96
650	49.92	1350	112.56	2050	180.58	2750	241.19	3450	287.51	4150	323.87	4850	351.78	5550	374.16
675	51.97	1375	115.04	2075	183.24	2775	213.06	3475	288.88	4175	324.7	4875	352.46	5575	374.36

Table 5.6-2 Standard Cubic Feet (scf) of natural gas compressed into one cubic foot of liquid volume at the given pressure.

A cascade system is comprised of three ASME (low, medium, high) high pressure storage vessels. Assume each of the vessels has a water volume of 46.3 ft^3, which would be 138.9 ft^3 total water volume. ASME storage vessels have a design pressure of 4,000 psi and a storage pressure of 3,600 psi. At 3,600 psi each storage vessel will contain 13,721 scf of natural gas (46.3 ft^3 * 296.34 scf / ft^3 water = 13,721 scf) at 70^{o}F. From Table 5.6-2 at 3,600 psi the water volume is 296.34 scf / ft^3. The total natural gas contained in the system if all three stages are at 3600 psi and 70^{o}F would be 41,163 scf (13,721 * 3).

The following assumptions have been made for the cascade sequence explanation:

1. Manual cascade system
2. Temperature remains constant
3. Each vehicle cylinder will contain 1,000 scf of natural gas at a pressure of 3000 psi
4. Each vehicle cylinder(s) is initially empty
5. No replenishment of the cascade bank during the refueling cycle

The liquid volume (empty) of the vehicle cylinders can be calculated by dividing the specified capacity at 3000 psi (1000 scf) by the amount of gas in scf (from Table 5.6-2) contained in $1 ft^3$ liquid volume at 3000 psi. So the total water volume of the vehicle cylinder would be 1000 scf / (259.67 scf / ft^3) = 3.85 ft^3. The cascade system should, at first, be assumed to be a single control volume containing all three storage banks. Between the pressures of 3600 psi and 3000 psi a usable volume from the cascade system would be 5095 scf (41,163 scf – 36,068 scf).

$$46.3 \text{ ft}^3 * 259.67 \text{ scf} / \text{ft}^3 * 3 = 36{,}068 \text{ scf.}$$

With a usable volume of 5095 scf in the cascade system, a total of five NGV's could be filled without the compressor having to recharge the cascade system.

$$5095 \text{ scf} / 1000 \text{ scf per NGV} = 5.095 \text{ NGV's}$$

Now, assume that the first NGV is ready to be serviced. The first vehicle can be completely filled from the low storage bank without having to switch to the next storage bank. The low bank contains 13,721 scf of natural gas at 3600 psi, after the first vehicle is serviced, the low bank will contain 12,721 scf (13,721 scf – 1000 scf) of natural gas at 3244 psi.

$$(13{,}721 - 1000) \text{ scf} / 46.3 \text{ ft}^3 = 274.75 \text{ scf} / \text{ft}^3$$

From Table 5.6-2 interpolate 274.75 scf / ft^3 to find the pressure in low storage bank (3244 psi) after the first NGV has been filled.

The second vehicle is now ready for service. The next vehicle can not be filled to the 3000 psi level from the low bank. The medium bank will now have to be used to 'top off' the vehicle. The second vehicle will initially be filled from the low bank until the pressure in the low bank and the NGV pressures equalize. The same mathematical process for the first NGV example must be done for the second.

$$(12{,}721 - 1000) \text{ scf} / 46.3 \text{ ft}^3 = 253.15 \text{ scf} / \text{ft}^3$$

From Table 5.6-2 interpolate 253.15 scf / ft^3 to find the pressure in the low storage bank (2911 psi). The pressure (2911 psi) is less than the desired 3000 psi fill level for the NGV. It is now necessary to determine the equalization pressure in the low storage bank and the second NGV to determine how much natural gas is needed from the medium bank.

$$12{,}721 \text{ scf} / (46.3 + 3.85) \text{ ft}^3 = 253.66 \text{ scf} / \text{ft}^3$$

Interpolate 253.66 scf / ft^3 from Table 5.6-2 to determine the equalization pressure (2918 psi) of the low storage bank and the second NGV cylinder. Since the low storage bank and the NGV are equalized, the NGV cylinder(s) now contain a pressure of 2918 psi (< 3000 psi), the NGV must be 'topped off' by the medium storage bank to achieve the desired 3000 psi fill level. The low bank now contains 11,744.41 scf (12,721 scf – 976.59 scf) of natural gas. The vehicle now contains 976.59 scf of natural gas.

$$3.85 \text{ ft}^3 * 253.66 \text{ scf} / \text{ft}^3 = 976.59 \text{ scf}$$

The medium storage bank must provide 23.41 scf (1000 scf – 976.59 scf) of natural gas to top off NGV number 2. The same mathematical process as before must be compiled to determine the pressure.

$$(13{,}721 \text{ scf} - 23.41 \text{ scf}) / 46.3 \text{ ft}^3 = 295.84 \text{ scf} / \text{ft}^3$$

Using Table 5.6-2, interpolate 295.84 scf / ft^3 to determine the total pressure remaining in the medium storage bank (3592.6 psi).

This method of calculating total volume and total pressure remaining can be applied to fill process from a cascade system for eight NGV's. The first eight vehicles can be filled from the low and medium storage banks only with the low storing bank containing (7280 scf at 1809 psi) and the medium storage bank containing (12,152 scf at 3047 psi) after the eight NGV's have been filled.

NGV number 9 will have to filled from the low, medium, and high storage banks. NGV number 9 will equalize pressure with low storage bank (1680 psi).

$$7280 \text{ scf} / (46.3 + 3.85) \text{ ft}^3 = 145.16 \text{ scf} / \text{ft}^3$$

Through interpolation using Table 5.6-2 the equalization pressure would be 1680 psi. After an initial fill from the low storage bank, 558.9 scf of natural gas would be contained in the NGV cylinder (3.85 ft^3 * 145.16 scf / ft^3).

NGV number 9 will now equalize pressure with the medium storage bank (2922 psi). With 12,152 scf remaining in the medium storage bank, the pressure in the medium storage bank and the NGV cylinder will equalize pressures.

$$(12{,}152 + 558.9) \text{ scf} / (46.3 + 3.85) \text{ ft}^3 = 253.46 \text{ scf} / \text{ft}^3$$

Through interpolation using Table 5.6-2 the equalization pressure would be 2922 psi. After the low and medium storage banks have gone through the equalization process, the high storage bank must be utilized to top off the vehicle. NGV number 9 now contains 975.82 scf (3.85 ft^3 * 253.46 scf / ft^3) of natural gas (3.85 ft^3 * 253.46 scf / ft^3). With the NGV containing 975.82 scf of natural gas, 24.18 scf (1000 scf – 975.82 scf) must be added to achieve the full fill level for NGV number 9. The high bank has a capacity of

13,721 scf of natural gas. The remaining natural gas in the high bank would be 13,696.82 scf (13,721 scf – 24.18 scf) at a pressure of 3592.3 psi.

$$13{,}696.82 \text{ scf} / 46.3 \text{ ft}^3 = 295.83 \text{ scf} / \text{ft}^3$$

Through interpolation, using Table 5.6-2, the pressure remaining in the third storage bank would be 3592.3 psi.

If this process is continued, 17 NGV's can be filled before this cascade system will need to be recharged. If a single control volume storage system (WVU physical plant) were used instead of cascading, only 5 vehicles could be recharged before the system would have to be replenished by the compressor. Table 5.6-3 compares the efficiencies of the two systems.

System	***Number of vehicles that can be fueled by the particular system***	***Natual gas capacity of each NGV (scf)***	***Natural gas capacity (scf) of system when fully charged***	***Efficiency of system = (# of vehicles * NG capacity of each NGV) / NG capacity of the system***
Cascade	17	1000	41,163	41.3 %
Single Control Volume	5	1000	41,163	12 %

Table 5.6-3 Efficiency comparisons of the cascade system and the single control volume system.

5.7 CNG Dispensers

The CNG from the storage bank is transported to a dispenser. The physical plant does not have an actual dispenser. The CNG fuel dispensing unit of the WVU physical plant NGV refueling station consists of nothing more than a steel box which houses two female nozzles and a supply pressure gauge. For this report, a dispenser is defined as the unit, which houses the electronic switches, digital readouts, and solenoid valves (for a cascade system) or dome load valves (single control volume storage bank) which control flow from the storage bank or cascade system, and the CNG supply hose and its components (valves, fittings, and nozzles) from the dispensing unit to the NGV. The WVU physical plant does not have the unit previously mentioned (electronic switches and solenoid valves), only the supply line with its components. The physical plant does not utilize a typical CNG fast fill dispenser. There are no electronic switches or solenoid valves on the dispensing section or final delivery point of CNG supply at the physical plant, which are normally present on publicly used CNG dispenser. The components of an NGV fueling system are illustrated in Figure 5.7-1. A brief description of the components of the NGV fueling system shown in Figure 5.7-1 are described in Table 5.7-1. All information contained in Table 5.7-1 and Figure 5.7-1 was provided by the Norwalk Company, Inc., South Norwalk, CT 06856. Notice, the physical plant fueling station does not use a storage cascade, quick fill dispenser, priority/ESD panel or a time fill hose assembly. The physical plant utilizes a dome load valve in place of the priority/ESD panel and dispenser unit, a single storage volume in place of the storage cascade.

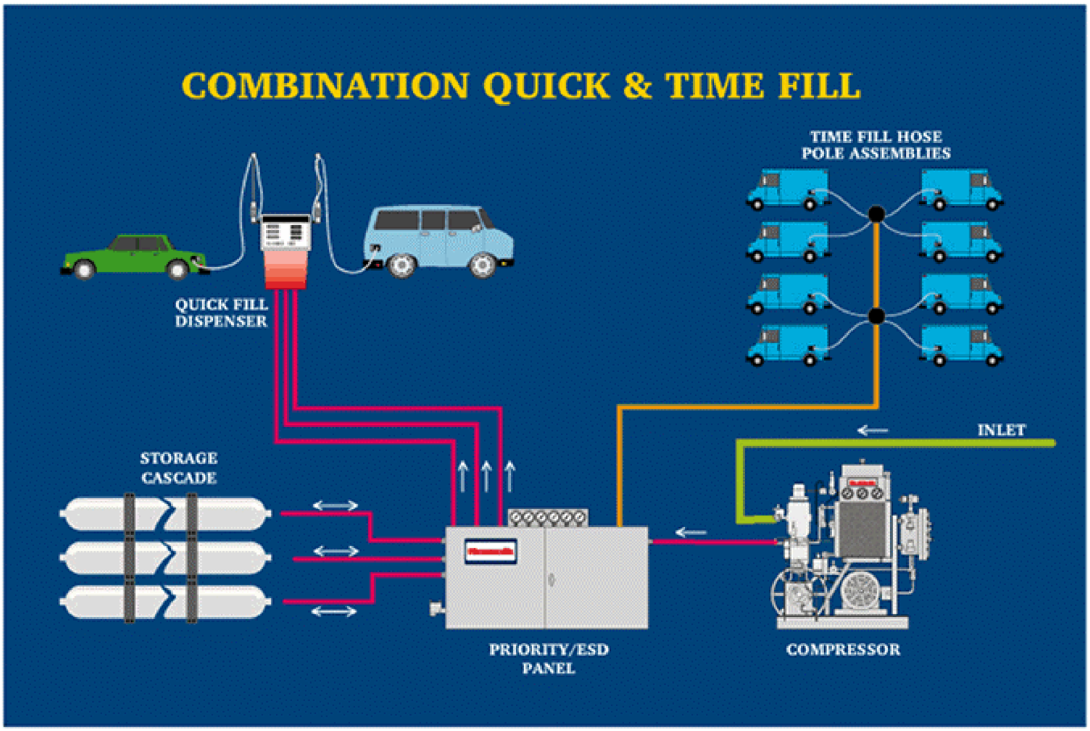


Figure 5.7-1Typical components of an NGV fueling system.

Component of the NGV fueling system ***(shown in* Figure 5.7-1*)***	***Description***
Quick Fill Or 'Fast Fill'	Used when the vehicle must be fueled in a time period and manner similar to that of liquid fuels. The compressor fills the cascade; from where gas is transferred to the vehicle via the compressor.
Time Fill	Used when some vehicles return to a central location, during which time they can be fueled. The compressor fills all the vehicles simultaneously via the hose poles.
Combination	Used when some vehicles return to a central location for fueling, while the balance of the fleet is not centrally garaged, and must be fueled in a short time period. This system combines both of the above features, and is the system depicted opposite. The appropriate configuration is determined by the fueling characteristic of the fleet and customer requirements. While the size and design of the facility may vary, the same basic features are usually incorporated into each system.
Quick Fill Dispenser	Meters and dispenses gas into the vehicle. A wide variety of dispensers are available, ranging from a simple cabinet with a digital display to a sophisticated microprocessor controlled dispensing system.
Storage Cascade	Used to store gas at a pressure higher than the vehicle storage pressure. This differential pressure is used to transfer the gas from the cascade into the vehicle. Cascades are available comprising of either DOT bottles or ASME vessels, (ASME vessels shown) depending upon the storage capacity required. The system is typically divided into three banks: high, medium, low. Any number of cascades can be connected together to increase storage capacity.
Priority/ESD Panel	Incorporates two separate systems: the PRIORITY SYSTEM, which is used to divert gas from the compressor to the appropriate component in the fueling system and the EMERGENCY SHUTDOWN (ESD) SYSTEM, which is used to isolate the storage cascade from the quick fill dispenser in the event and ESD button is depressed.
Gas Dryer (not shown)	Used to remove water vapor from the gas and to dry it to a pressure dew point, which meets local conditions.
Time Fill Hose Assemblies	Used to transfer gas from the compressor/distribution system into the vehicles. They are available in single, dual, or four hose versions and are normally unmetered.

Table 5.7-1 Description of Components of an NGV Fueling System.

Although this report deals with the quick fill or fast fill process, the time fill hose pole assembly illustrated in Figure 5.7-1 is a system that takes several hours to fill an NGV rather than an a couple of minutes. When using the time fill process to fill an NGV, the NGV is usually filled with CNG on an over night basis. The time fill is a simple method for fleet vehicles to be refueled.

As mentioned, the physical plant CNG dispensing site contains two female fuel supply nozzles. The two nozzles are Snap-tite® and Parker Hannifin® nozzles, and are mounted on two separate fuel supply lines from the storage bank. There are two available nozzles because there is no universal fitting that can be used for all NGV's. The physical plant NGV fleet has NGV's that utilize the Snap-tite® nozzle or the Parker Hannifin® nozzle. The fact that there is no universal nozzle creates a large problem in CNG public acceptance. This is a problem that the entire CNG market faces. It is not an issue that affects the physical plant only. For example, if a person that drives an NGV wants to do any long distance traveling it could be a problem if an out of town CNG dispenser does not have a nozzle that fits that person's particular nozzle for their NGV. That is an issue that needs to be addressed as a step in gaining national acceptance of NGV's.

Reconfirming, the physical plant does not have a normal dispenser unit. The dispenser at the physical plant was not intended for public use. CNG dispensers at public fueling stations provide similar information to the user as a public gasoline dispenser. A CNG dispenser at a public service station provides information to the person refueling his or her NGV. The information provided to the person by the dispenser at a public facility usually includes, at a minimum, the cost per GGE (Gasoline Gallon Equivalent) of CNG, the total amount of CNG dispensed in GGE, and the dollar amount of CNG dispensed.

An example of the common information for the user to see on a public dispenser is shown in Table 5.7-2. An illustration of a public NGV dispenser which is located at the BP® service station located in Westover, WV is shown in Figure 5.7-2 which provides the information mentioned in Table 5.7-2. An illustration of the dispenser at the physical plant is shown in Figure 5.7-3.

Cost per GGE (Gasoline Gallon Equivalent) of CNG	**Quantity of CNG dispensed in (GGE's)**	**Dollar cost of CNG sale**
\$1.24 / GGE	2	\$2.48

Table 5.7-2 Dispenser information commonly available to user at a public CNG fueling station.

Figure 5.7-2 A publicly used CNG dispenser for NGV's located at BP® in Westover, WV.

Figure 5.7-3 CNG dispenser utilized by the WVU physical plant.

All CNG dispensers have a valve that is used to allow CNG to flow from the CNG storage bank through the nozzle on the dispenser, which will be connected to the nozzle on the NGV to the fuel storage tanks onboard the NGV. If there is a unit that houses the electronics, which were mentioned earlier in this subsection, the CNG flows through this unit. This valve is common on public CNG dispensers as well as the dispenser at the WVU physical plant. The valve used at CNG dispensers is a '½ turn' ball valve, which has a motion of 180^{o}. The valve has three positions: on, off, and vent. When the valve is in the 'on' position the CNG is free to flow through the valve and then through the dispenser supply nozzle if it is correctly coupled with the NGV. As mentioned in section 5.3.2, the CNG will not flow through the dispenser nozzle unless there is a perfect female to male connection. If the dispenser valve is in the 'off' position, CNG cannot flow through the valve. The CNG supply form the storage bank is blocked by the dispenser valve, while it is in the 'off' position. The dispenser valve should be left in the 'off' position when a person is finished filling their NGV with CNG. If the dispenser is in the 'vent' position, CNG is vented from the line. The CNG that is vented is just the CNG that is located between the dispenser valve and the dispenser fill nozzle. CNG gets trapped in between the two devices because there is check valve built into the dispenser nozzle. If the space between the dispenser valve and the dispenser nozzle could not be vented, then it would be impossible to uncouple the dispenser female nozzle and the male NGV nozzle as mentioned in section 5.3.2. The physical plant uses only the dispenser valve to initiate flow to the NGV.

On public CNG dispensers, the same style dispenser valve is used, but an on/off switch is commonly present on the exterior of the CNG dispenser itself. The switch needs to be in the ‘on’ position before the CNG will flow to the dispenser valve. A solenoid valve is controlled by an ‘on/off’ switch controlled by a store clerk is located inside the dispenser, which permits CNG to flow through the dispenser. The store clerk should be notified to turn that switch on if has not already been actuated. Once the clerk turns the dispenser ‘on’ the dispenser valve should be turned to the ‘on’ position then the ‘on/off’ electrical switch located on the exterior of the CNG dispenser should be closed which allows the fill process to begin. The aforementioned dispenser valve in the ‘on’, ‘isolated’, and ‘vent’ position is shown in Figure 5.7-4. A small panel underneath the valve, which indicates dispenser valve position, was slightly damaged from unknown causes, which may make it difficult for a user to see what it says.

Figure 5.7-4 Illustration of dispenser valve in the 'on', 'isolated', and 'vent' positions respectively from bottom picture to top picture.

5.8 An Understanding of How to Set Up the Transportable Experimental Testing Apparatus

The experimental test apparatus discussed in throughout this chapter can be entirely transportable. Since the experimental apparatus is not stationary, it is a fully transportable system that can be taken to any NGV refueling station to do full scale testing. The experimental apparatus is a valuable piece of equipment because it can determine the characteristics of the fill process for any NGV refueling station that it is utilized at.

The experimental apparatus or test rig is simple to assemble. The test rig consists of nothing more than the test manifold mentioned previously in this chapter and illustrated in Figure 5.1-1. A step by step procedure makes the test rig simple to assemble which is discussed in Table 5.8-1.

Step #	***Function***
1	Place the test cylinder in the wooden case and place the combination on the ground.
2	Swing the wooden arm on the wooden case to the vertical position.
3	Attach the female fitting end of the manifold to the male fitting (on the cylinder valve).
4	Wrap a 'bungy cord' around the vertical arm and the test manifold (to compensate for any strain present when the dispenser hose is attached to the manifold).
5	Plug the two female yellow type K thermocouple plugs into the SMCJ-K reference junction. One plug per SMCJ-K
6	Attach the leads (with female connectors already on their ends) from the Analog Devices RTI-815 DAQ card terminal board or back plane to the male connectors on the output side of the SMCJ-K reference junction. -The thermocouple inside the test manifold is designated as channel 1 -The thermocouple inside the test cylinder is designated as channel 4
7	Attach the excitation leads of the (PX-41) pressure transducer to the 1st 24 volt DC power supply (assume that the output leads from the sensor are already attached to the RTI-815 back plane). -The pressure transducer is designated as channel 2.
8	Attach the excitation leads of the flow meter signal conditioner to the 2nd 24 volt DC power supply (assume that the output leads from the sensor are already attached to the RTI-815 back plane). -The flow meter is designated as channel 3.
9	Double check to make sure that all connections are correct and secure. Assume that the computer is already hooked up and ready to go but not powered up.
10	Connect the ground wire to the computer and to the test manifold. A terminal end can be used to attach the ground wire to the back of the computer. And the Bleeder valve has a nut that can be used to secure the other end of the ground wire to the test manifold.
11	Plug the two 24 volt power supplies, the computer CPU, and the computer monitor into a power strip. Plug the power strip into an AC power outlet (110 volt – 120 volt). If a power outlet is not available a generator (with a 'noise' eliminator) can be supplemented.
12	Attach the dispenser hose to the test manifold. Turn the valve to the 'on' position. A small surge on CNG will dispense tank.
13	'Boot up' the computer. The computer utilized for this experimental apparatus used Microsoft® Windows 98 as an operating system. DOS is sufficient to execute the data acquisition. The user must enter the DOS operating system anyway. Once in DOS, the user will be confronted with the 'C:' prompt. At this prompt type in QBASIC. DOS will enter the QBASIC subdirectory, at that point type QB. The computer has now gone to the QBASIC interface. Go to 'open' on the file menu. Open the file 'GASPUMP2.EXE'. Once the program has opened press the F5 key on the computer keyboard to execute the program. Once the computer has started execution it will wait until flow is present before it will start logging data. When flow stops, the program automatically stops taking data. All data is sent to a data file 'GASPUMP2' in the QBASIC subdirectory
14	To disassemble, perform steps 1-13 in reverse order.

Table 5.8-1 How To Assemble and Disassemble the Transportable Experimental Test Rig.

6 Test Results

Several tests at varied ambient temperatures were performed in order to better understand the CNG fast fill process. Tests were performed at varying temperatures to determine the affects of ambient temperature on the ability to provide a desirable fill level. As mentioned in chapter 4, the dome load valve, which the physical plant utilizes will consistently under fill an NGV at an average of 6 – 20%. For the industry to develop a system that can provide a 100% full fill to any NGV, a knowledge of the process that is taking place needs to be understood.

Knowing the temperature, pressure, flow rate, and volume through out the fast fill process is important to help explain what is happening to the CNG during the fill process. As mentioned in chapter 5 a test manifold was built, which measured temperature, pressure, and flow rate during the fill process. The temperature inside an NGV fuel storage cylinder was also collected. The NGV cylinder was placed in a thermal bath for at least an over-night period of time, which was nothing more than leaving the cylinder outside over night. By leaving the cylinder outside all night, it allowed the cylinder to be at the same temperature as the storage supply from the NGV refueling station. With both the storage cylinders and the NGV cylinder at approximately similar temperatures to ambient at the start of the fill process, it was then possible to determine the characteristics of the CNG during the fast fill process. For example, if the test cylinder and/or test manifold were left indoors during the winter, and taken to do tests without thermally equalizing the cylinder and test manifold to ambient environment the data could have been distorted. Upon having the system as close to thermally equalized as possible, testing could be performed to better determine characteristics of CNG during the fast fill process as well as characteristics of CNG during the fast fill process versus ambient temperature change.

6.1 Temperature Change in Test Manifold and Test Cylinder During the Fast Fill Process.

A review of the temperature in the test manifold along with the internal test cylinder temperature is illustrated in this section. Tests (temperature versus time) compiled at the WVU physical plant refueling station were taken from the single control volume style CNG supply system. This subsection does not display any information concerning the temperature versus time data for the cascade system, which will be discussed in the following subsection.

Temperature in the test manifold and the test cylinder varied greatly during the fast fill process. The Joule-Thomson cooling effect was discovered to be much more evident when the temperature data was collected from the test manifold thermocouple. The Joule-Thomson cooling affect did not appear to be present during any temperature data recorded via the test cylinder thermocouple. The Joule-Thomson cooling affect that took place inside the test manifold appeared to be greater in magnitude as the ambient temperature decreased.

The temperature change that took place in the test cylinder appeared to be simply heat increase versus time due to heat of compression of the natural gas from whichever supply system the CNG was flowing from. A steady increase in temperature appeared to take place in the cylinder during the fill process whether the CNG was injected from the cascade system or the single control volume storage system. A steady increase temperature trend line was present during cold and hot ambient testing conditions. The results of the temperature versus time, based on ambient temperature change, graphical representations for single control volume storage (6.1.1) and cascade storage supply (6.1.2) systems are illustrated in the following two subsections.

6.1.1 Temperature versus Time Tests Compiled from a Single (Control) Volume CNG supply system.

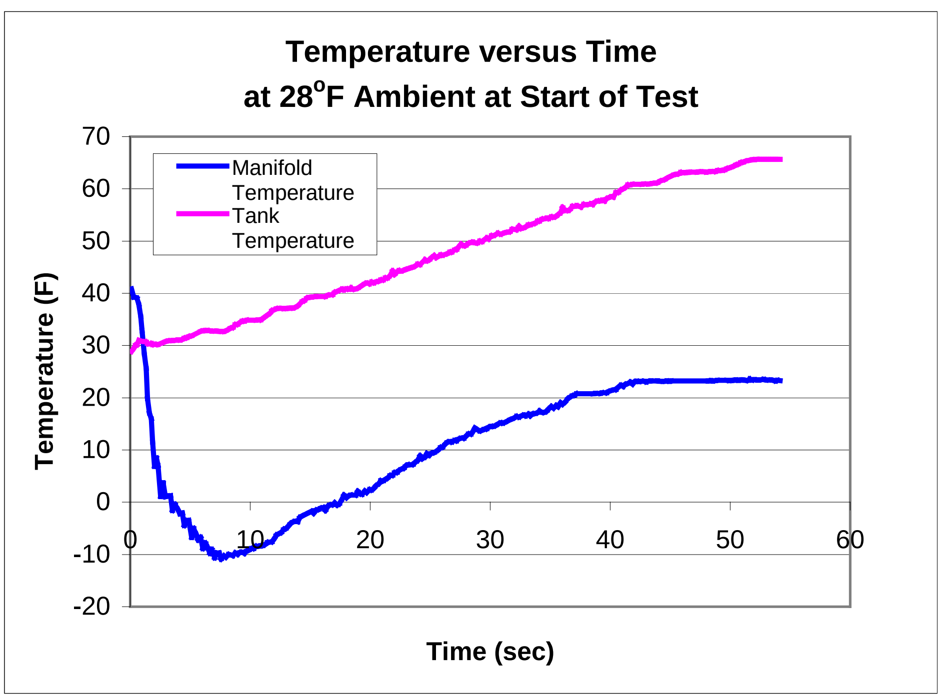


Figure 6.1-1 Temperature versus Time at 28°F Ambient at Start of Test.

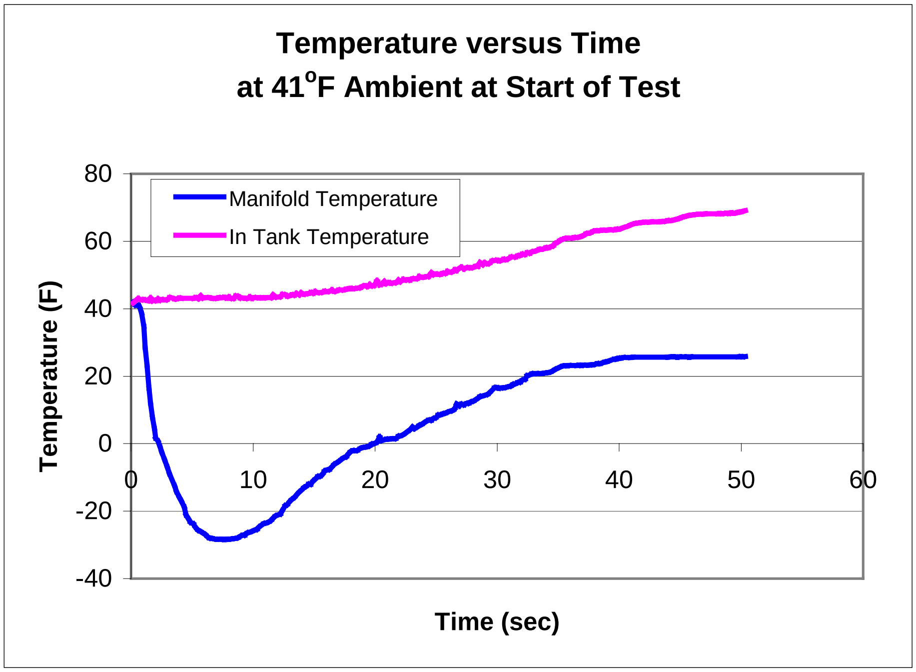


Figure 6.1-2 Temperature versus Time at 41°F Ambient at Start of Test.

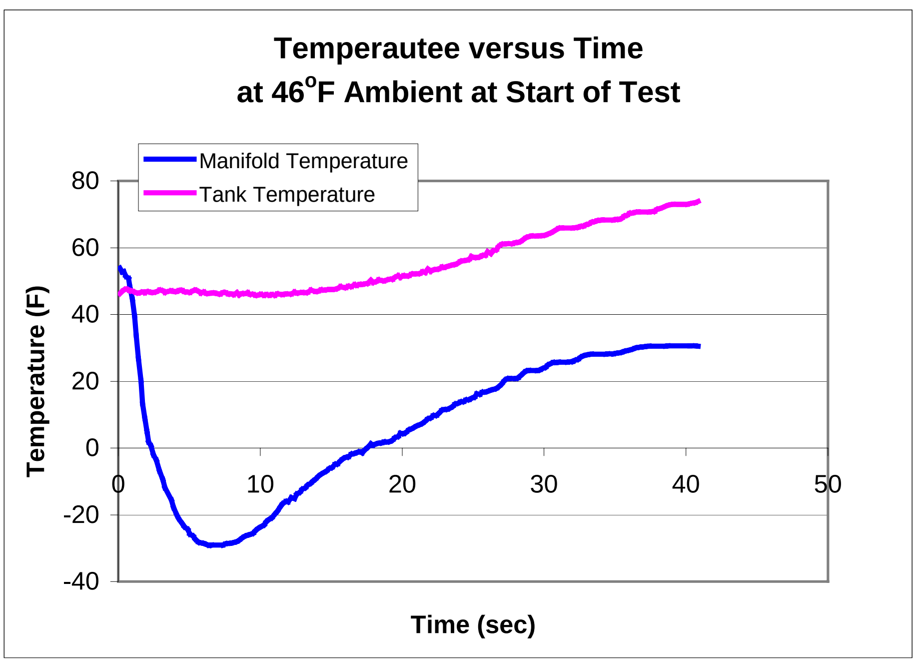


Figure 6.1-3 Temperature versus Time at 46°F Ambient at Start of Test.

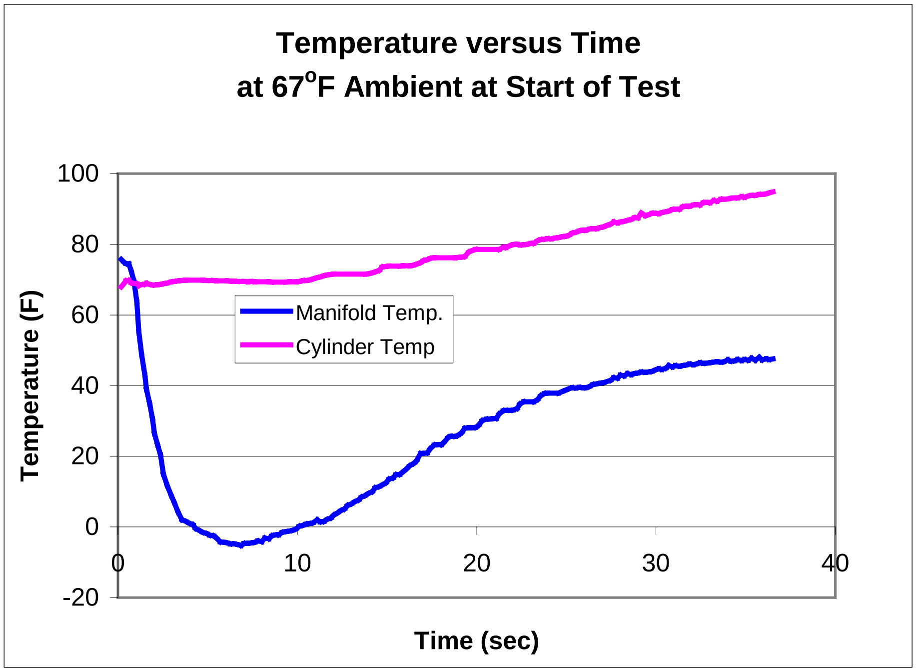


Figure 6.1-4 Temperature versus Time at 67°F Ambient at Start of Test.

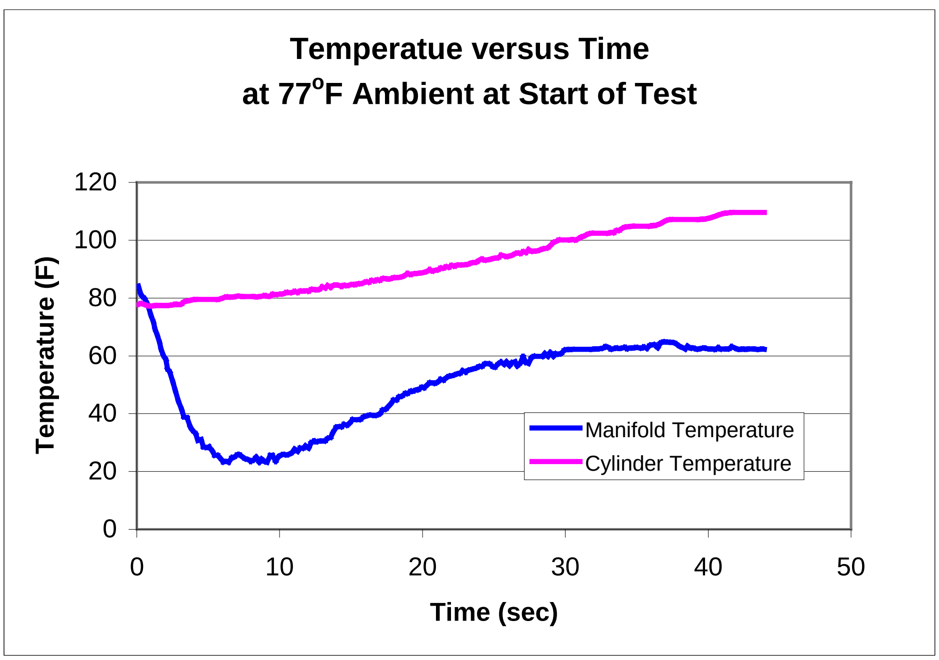


Figure 6.1-5 Temperature versus Time at 77°F Ambient at Start of Test.

6.1.2 Temperature versus Time Tests Compiled from a Cascade Storage CNG supply system.

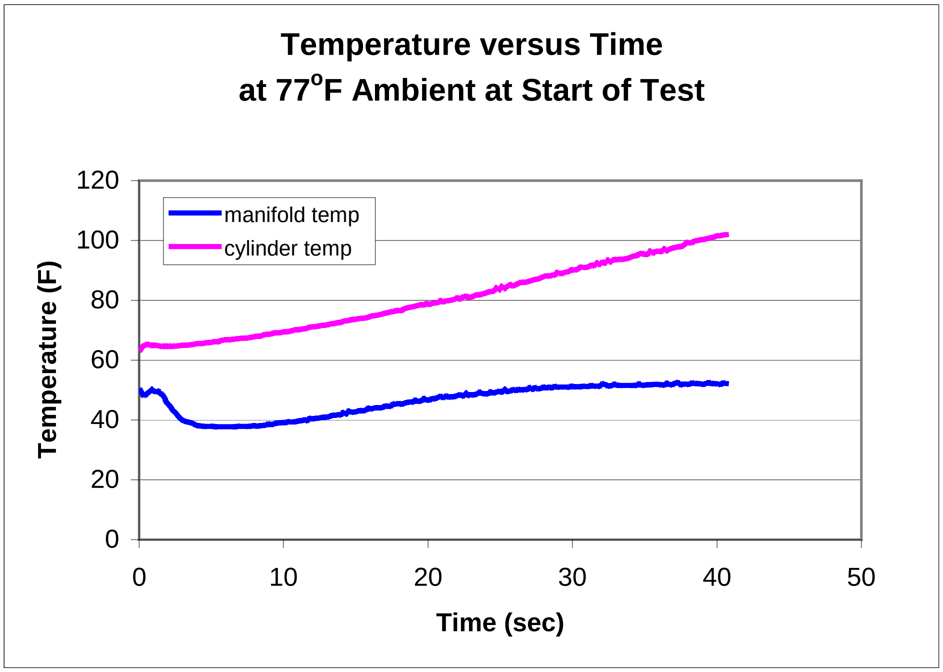


Figure 6.1-6 Temperature versus Time at 77°F Ambient at Start of Test.

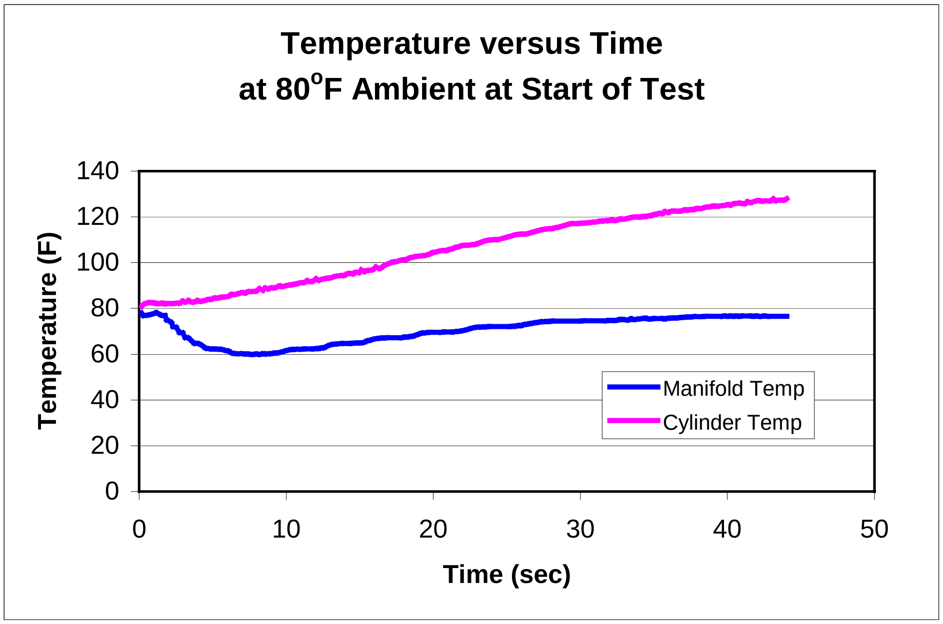


Figure 6.1-7 Temperature versus Time at 80°F Ambient at Start of test.

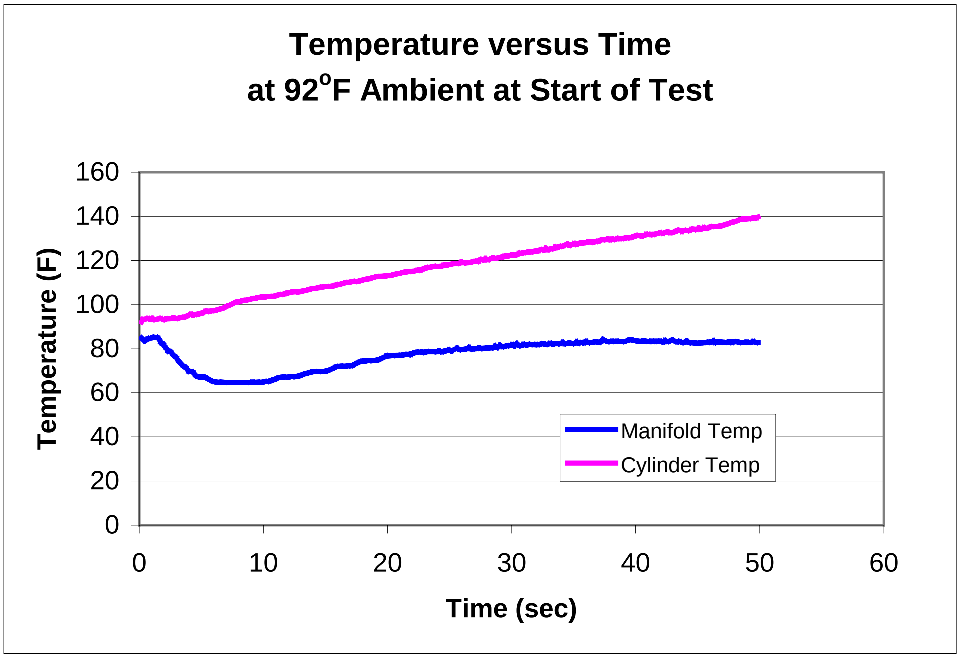


Figure 6.1-8 Temperature versus Time at 92°F Ambient at Start of Test.

6.2 Pressure Change during the Fast Fill Process.

The pressure curve for the fast fill process versus time was similar in shape during every test that was compiled. Graphical representations of pressure versus time for the single control volume and the cascade storage supply are illustrated in following two subsections. The final charge pressure dispensed to the test cylinder was dependant upon whether or not the compressor had fully charged the CNG storage supply. The warmer the ambient weather, the less the compressor had to operate to maintain a full charge to the CNG storage supply (single control volume or cascade) if a steady line of NGV's were not being dispensed. If a steady line of NGV's were being filled then a compressor would obviously have to operate on a more regular basis to maintain a desirable pressure on the storage system. The results in the following two subsections indicate that a desired charge to the test cylinder of 3000 psi (from single control volume) and a final charge of 3600 psi (from cascade system) was not met at any point for any tests compiled.

6.2.1 Pressure Changes during Fast Fill Process Compiled from the Single Control Volume Storage Supply.

The compressor station at the WVU physical plant delivered final charge pressures ranging from (2055 psi – 2894 psi), which was well below the desired final charge of 3000 psi. The average final charge pressure for the five data sets discussed was found to be 2576 psi. The final charge pressure dispensed to the test cylinder did vary as ambient temperature changed. However, the final charge pressure dispensed to the test cylinder was not entirely dependent upon ambient temperature change. There was not a linear relationship of final pressure charge based upon ambient temperatures, however the test set up was not able to directly measure affects of ambient temperature alone. It was difficult to determine direct effects of ambient temperature change on final charge pressures because the supply CNG from the single control volume storage supply was not always maintained at full capacity. The compressor at the WVU physical plant NGV refueling station did not run in ‘automatic’ mode at all times to ensure the storage supply pressure was maintained to the proper level, but turned on manual by physical plant employees on an as needed basis. So, the colder the ambient if the compressor was not automatically maintaining the storage supply pressure at the desired level, the storage supply pressure was greatly affected by ambient temperature conditions. By not having the control volume storage supply maintained close to full capacity (3600 psi), the final charge pressure dispensed to the test cylinder was consistently low, and a direct ambient temperature affect could not be accurately monitored. The dome load valve affected final charge pressures, which did take ambient whether conditions into consideration. The rest of this subsection is compiled of graphical illustrations of pressure change versus time elapsed during the fast fill process.

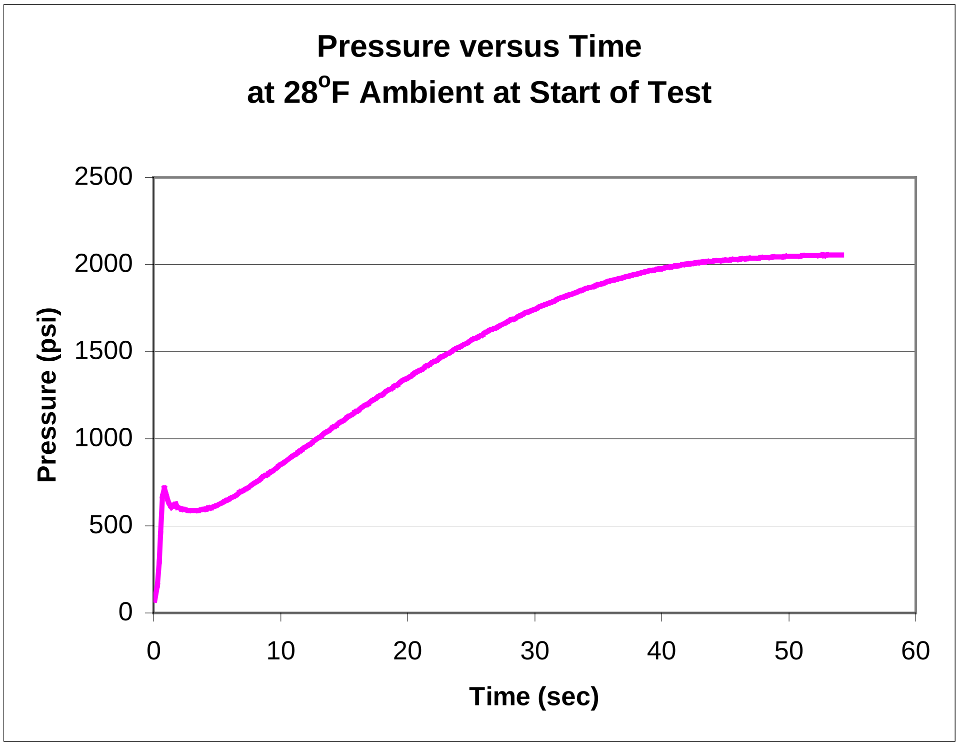


Figure 6.2-1 Pressure versus Time at 28°F Ambient at Start of Test.

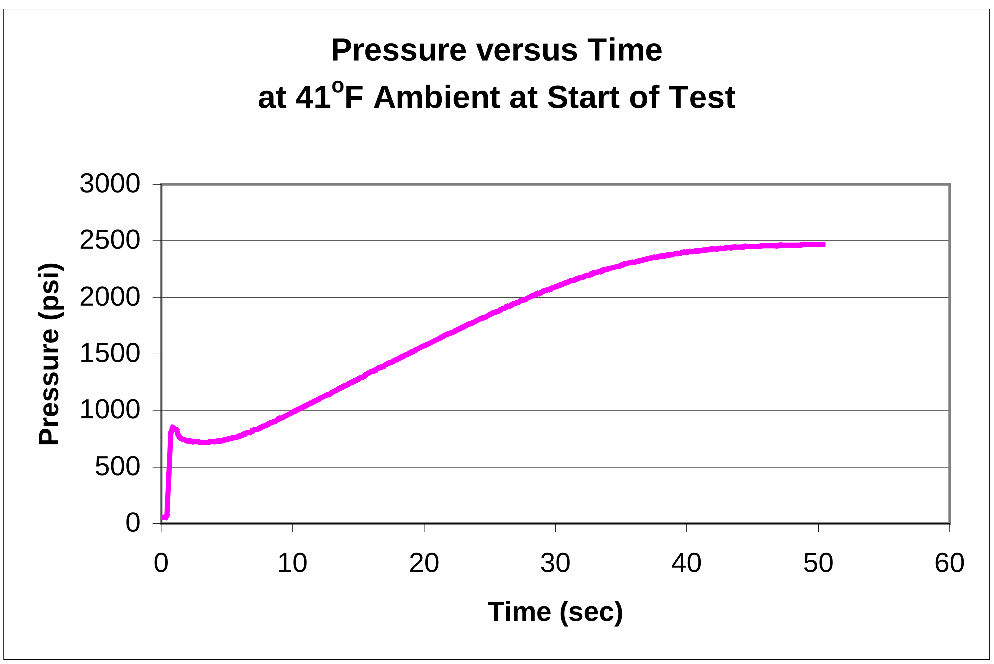


Figure 6.2-2 Pressure versus Time at 41°F Ambient at Start of Test.

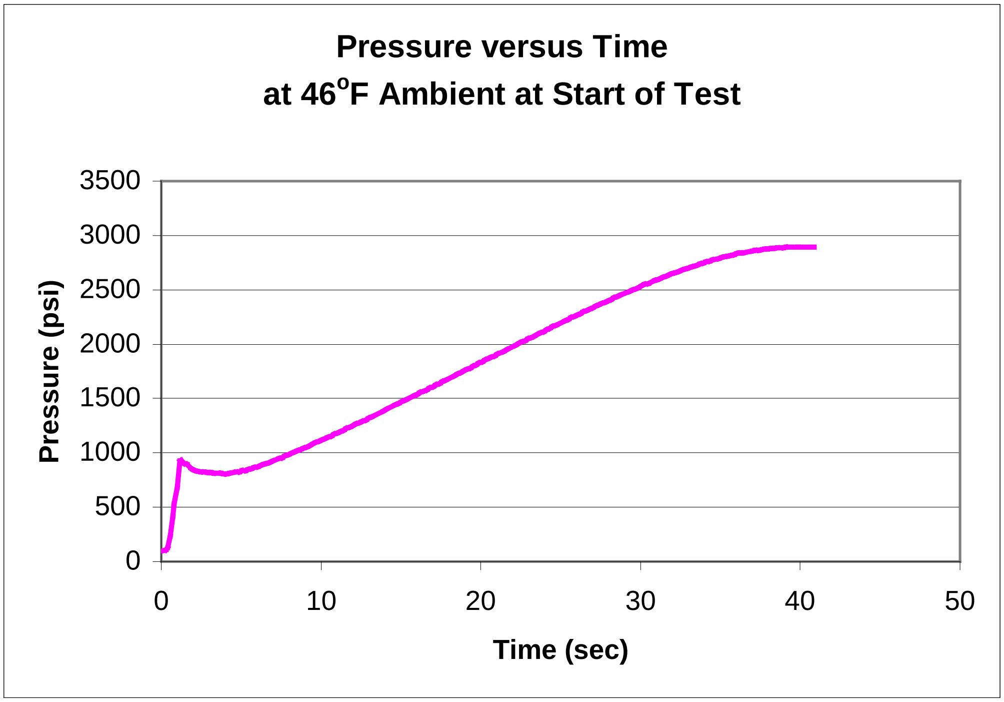


Figure 6.2-3 Pressure versus Time at 46°F Ambient at Start of Test.

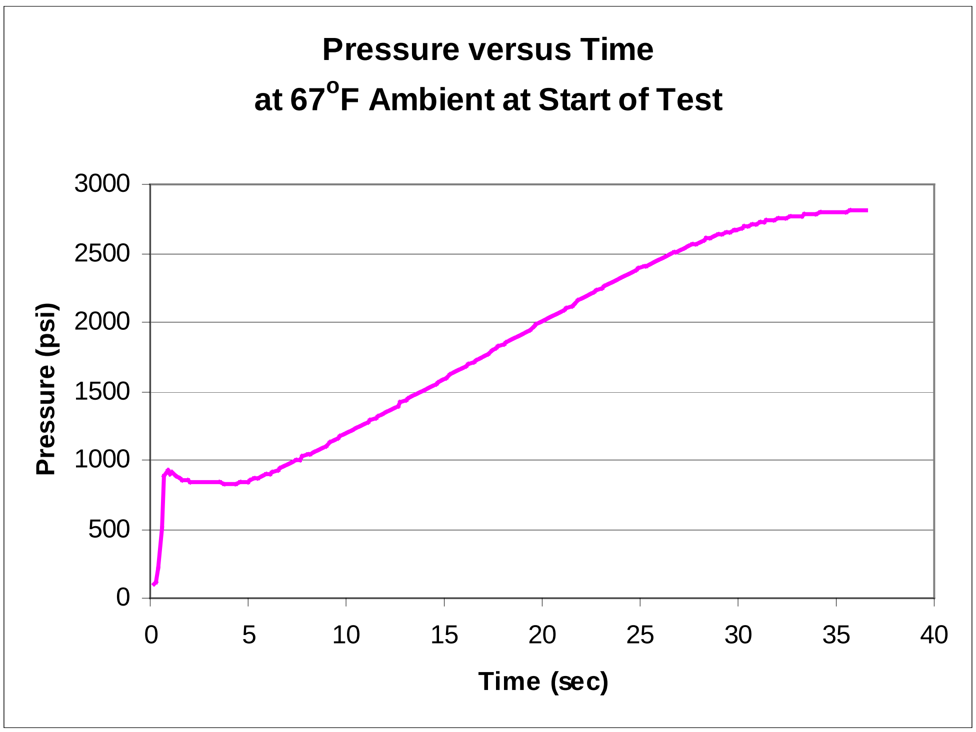


Figure 6.2-4 Pressure versus Time at 67°F Ambient at Start of Test.

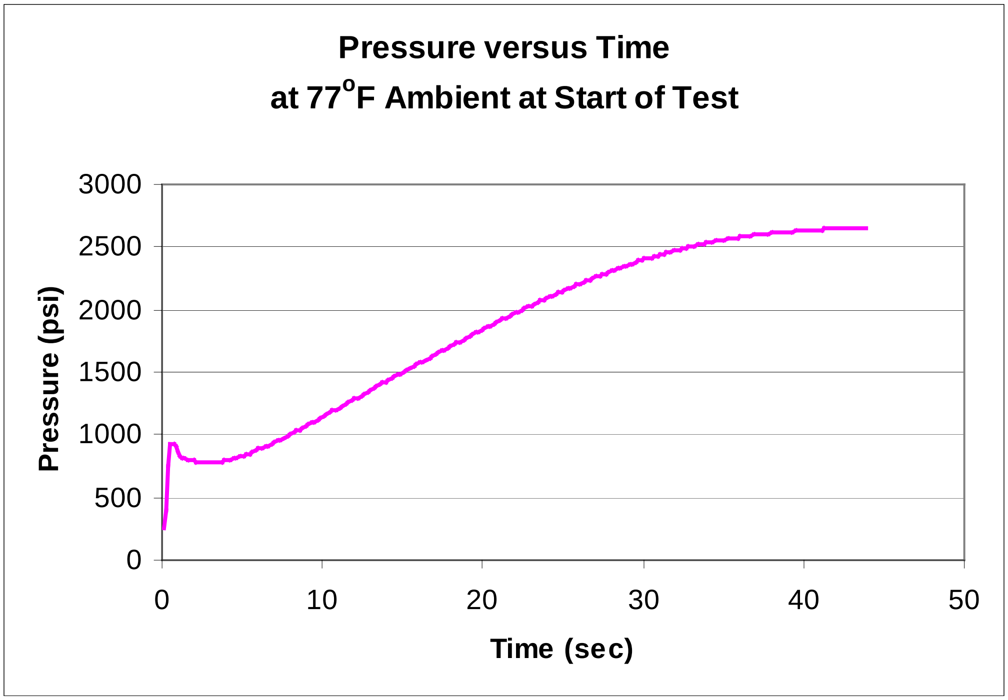


Figure 6.2-5 Pressure versus Time at 77°F Ambient at Start of Test.

6.2.2 Pressure Changes During Fast Fill Process when compiled from the cascade storage CNG supply system.

The compressor station at the BP® station in Westover, WV delivered final charge pressures ranging from (3365 psi – 3427 psi), which was below the desired final charge of 3600 psi. The average final charge pressure for the three data sets discussed was found to be 3388 psi. The final charge pressure dispensed to the test cylinder, again, did vary as ambient temperature changed. However, the final charge pressure dispensed to the test cylinder was not entirely dependent upon ambient temperature change as in the case single control volume. There was not a linear relationship of final pressure charge based upon ambient temperatures, however the test set up was not able to directly measure affects of ambient temperature alone. It was difficult to determine direct effects of ambient temperature change on final charge pressures because the supply CNG from the single control volume storage supply was not always maintained at full capacity. By not having the control volume storage supply maintained close to full capacity, the final charge pressure dispensed to the test cylinder was consistently low, and a direct ambient temperature affect could not be accurately monitored. The rest of this subsection is compiled of graphical illustrations of pressure change versus time elapsed during the fast fill process.

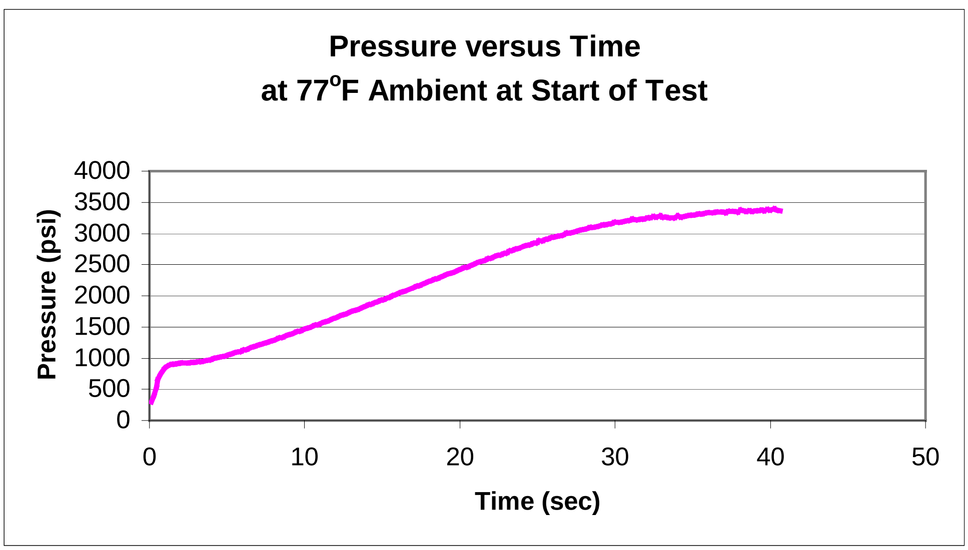


Figure 6.2-6 Pressure versus Time at 77°F Ambient at Start of Test.

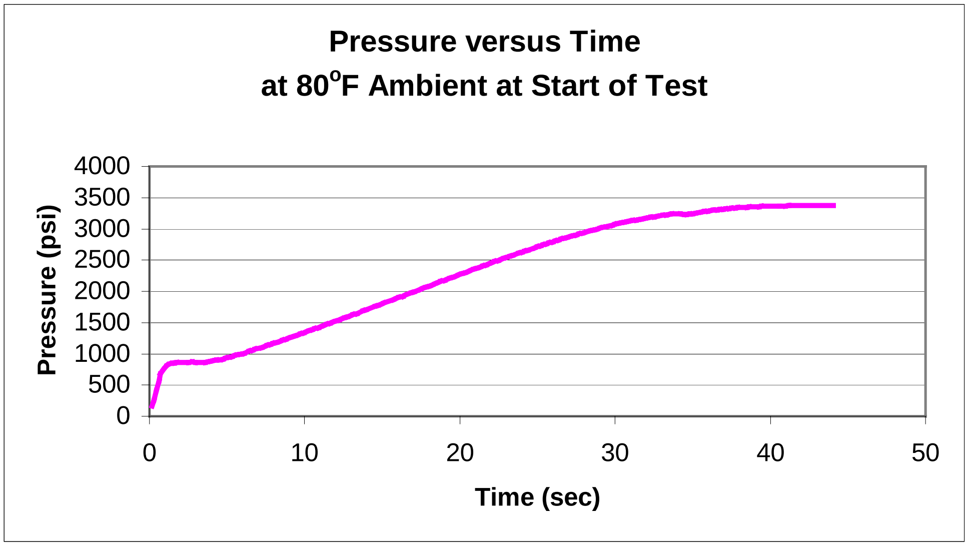


Figure 6.2-7 Pressure versus Time at 80°F Ambient at Start of Test.

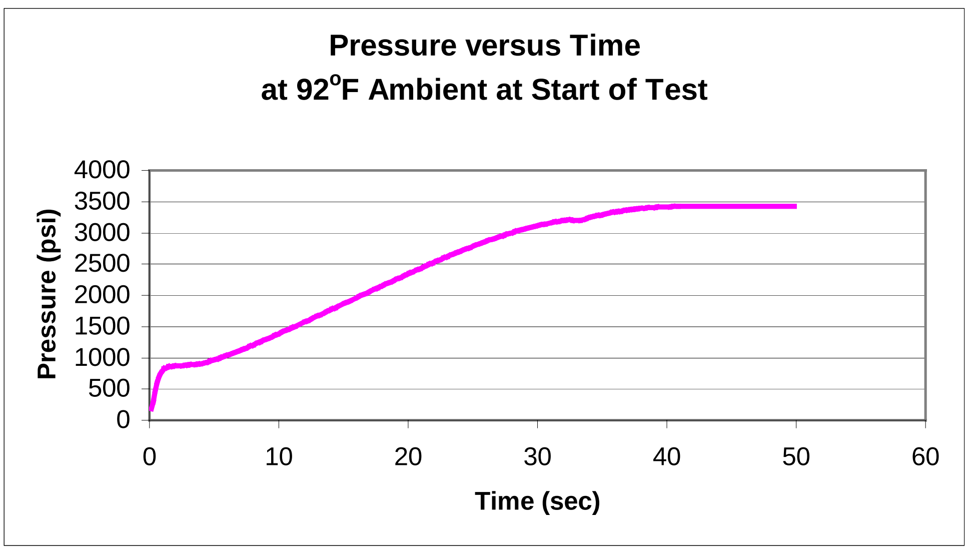


Figure 6.2-8 Pressure versus Time at 92°F Ambient at Start of Test.

6.3 Flow Rate Changes During the Fast Fill Process.

The flow rate during the fast fill system was measured in GGE/min (Gasoline Gallon Equivalent per minute) CNG flow from the whichever storage supply that was being monitored. The flow rate changes versus time elapsed had a similar flow rate curve. The flow rate curves were unique for each particular application (single control volume and cascade supply). As the valve from the dispensing unit from either compressor station was opened, a rapid flow of CNG was present immediately. After the immediate huge rush of CNG into the test cylinder was measured, the CNG flow appeared to continuously decrease through out the rest of the fill process until flow ceased. For tests compiled on the cascade system, a second curve was noticed. The second curve was similar in appearance to the original curve but smaller in magnitude. The second curve indicated that the next storage bank in the cascade system had been activated by the ESD/priority panel to 'top off' the cylinder. Flow rates from the single control volume storage supply ranged from .68 GGE/min to 1.80 GGE/min with an average flow rate of 1.22 GGE/min over the five tests observed at the WVU physical plant. Flow rates from the cascade storage supply ranged from 1.32 GGE/min to 1.75 GGE/min with an average flow rate of 1.5 GGE/min for the three tests observed at the BP® station in Westover, WV. The average flow rate was directly proportional to the pressure delivered to the test cylinder. The flow rate test results can be observed in the following two subsections.

'Choked Flow' did not occur during the fast fill process. Choked flow is defined as "neither the pressure variation within the nozzle nor the mass flow rate is affected

(Moran, Shapiro, [30]).” A graphical description of choked flow is illustrated in Figure 6.3-1.

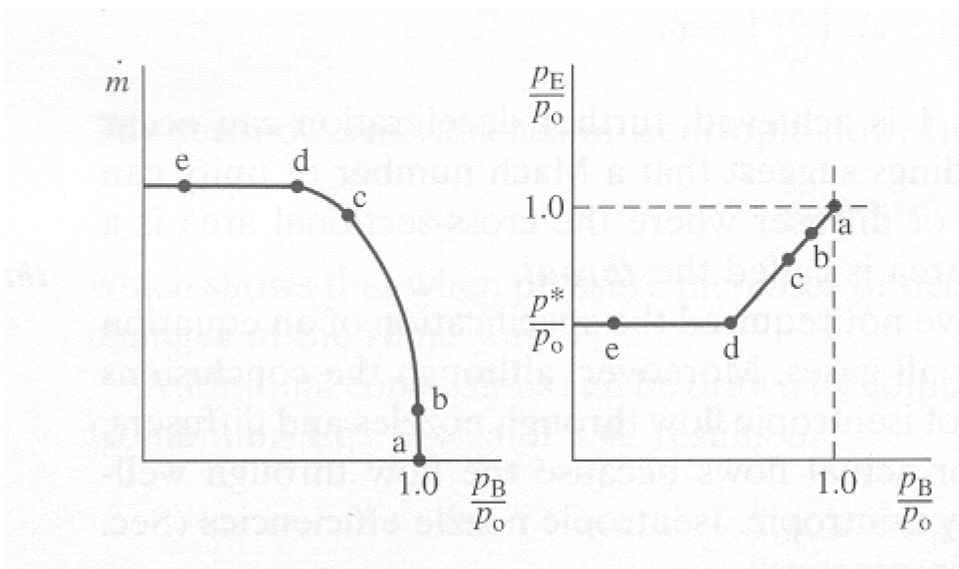


Figure 6.3-1 Illustration of Choked Flow.

Where $\bar{m}$ = mass flow rate of CNG to the test cylinder, p_B = back pressure (pressure in the exhaust region outside the nozzle), p_o = stagnation pressure, p_E = exhaust pressure, and p^* = critical pressure (point d).

6.3.1 Flow Rate Changes During the Fast Fill Process Compiled from the Single Control Volume CNG Storage Supply.

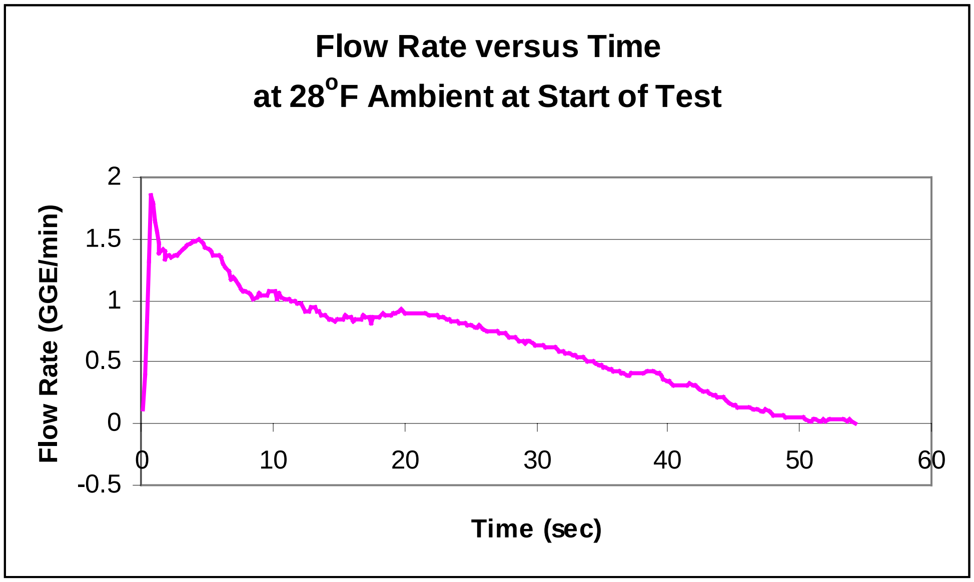


Figure 6.3-2 Flow Rate versus Time at 28°F Ambient at Start of Test.

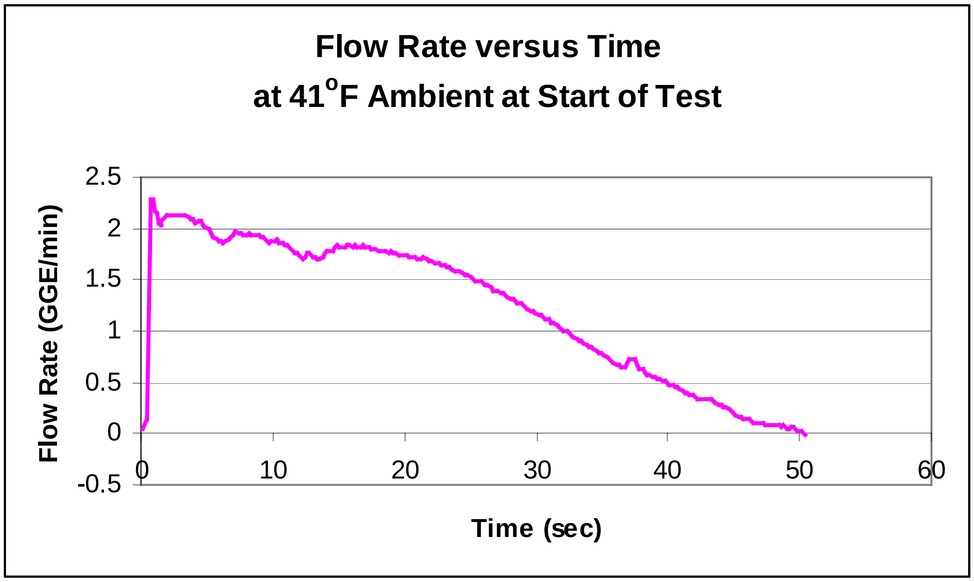


Figure 6.3-3 Flow Rate versus Time at 41°F Ambient at Start of Test.

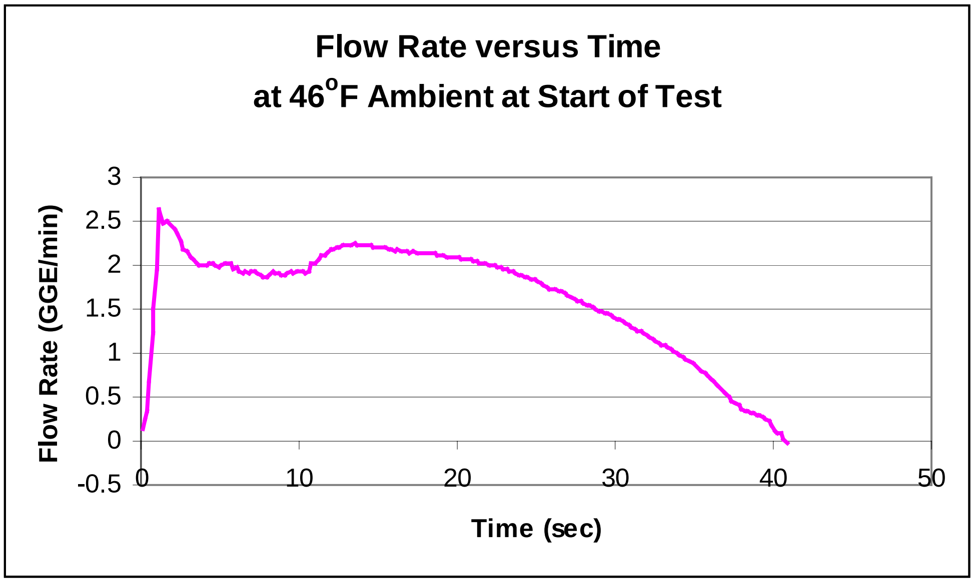


Figure 6.3-4 Flow Rate versus Time at 46°F Ambient at Start of Test.

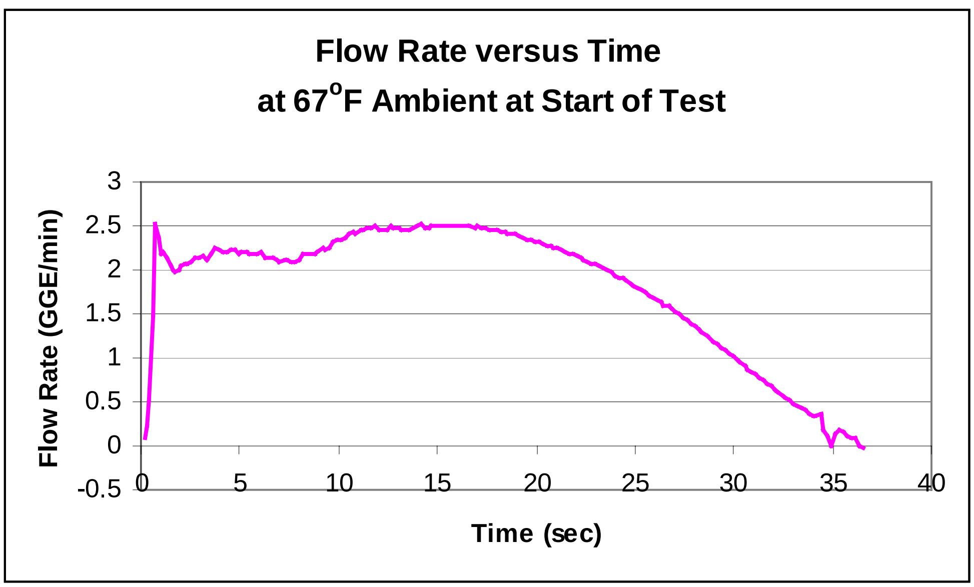


Figure 6.3-5 Flow Rate versus Time at 67°F Ambient at Start of Test.

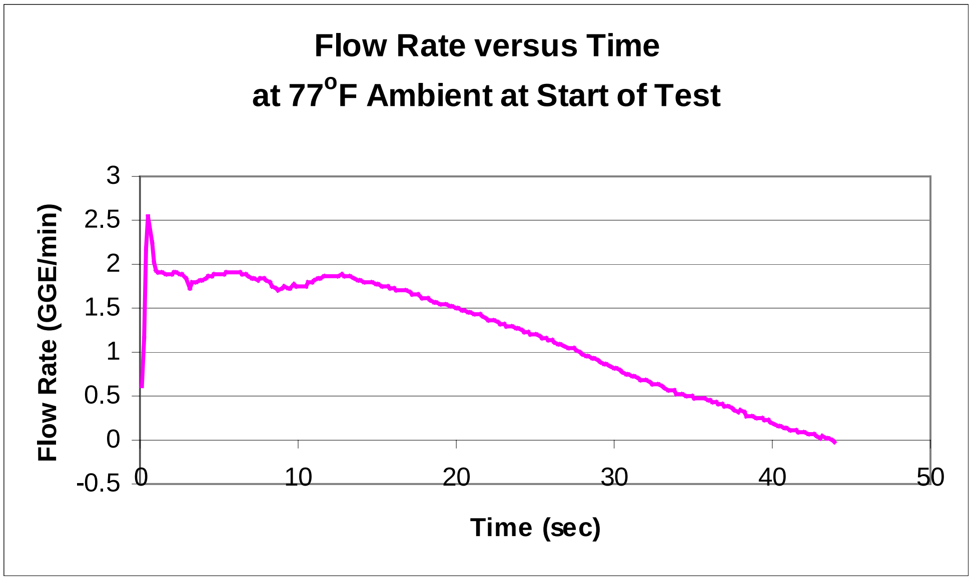


Figure 6.3-6 Flow Rate versus Time at 77°F Ambient at Start of Test.

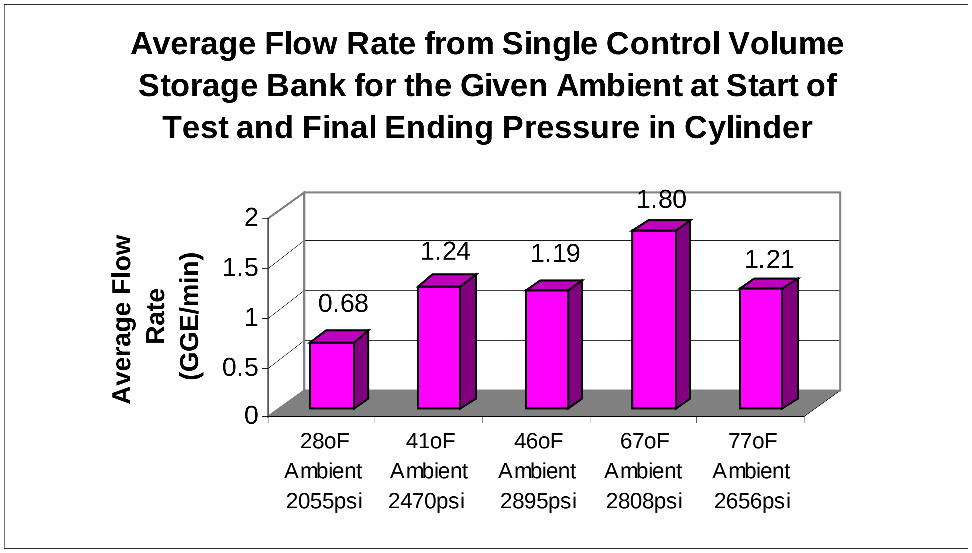


Figure 6.3-7 Average Flow Rate for a Given Ambient and Final Pressure.

6.3.2 Flow Rate Changes during Fast Fill Process Compiled from Cascade CNG storage supply.

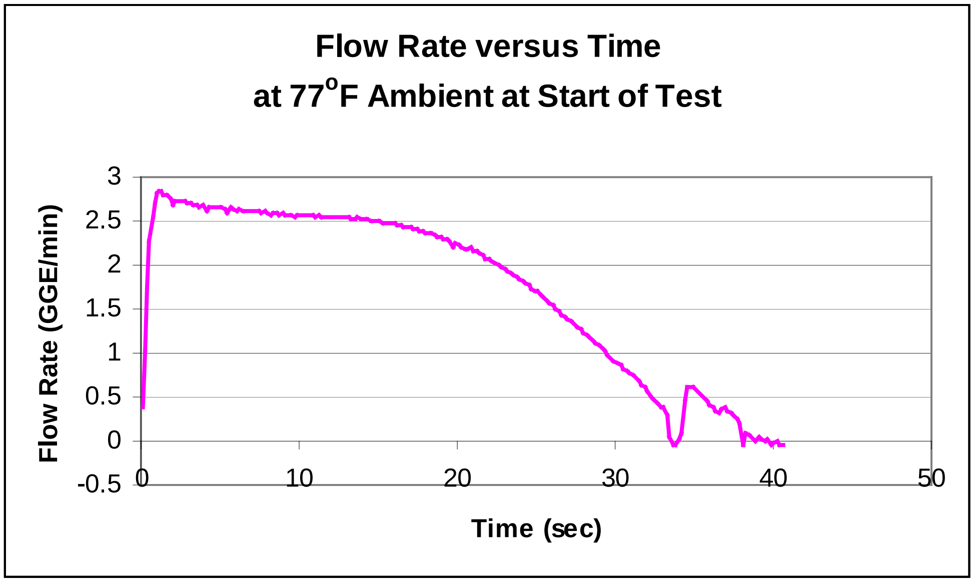


Figure 6.3-8 Flow Rate versus Time at 77°F Ambient at Start of Test.

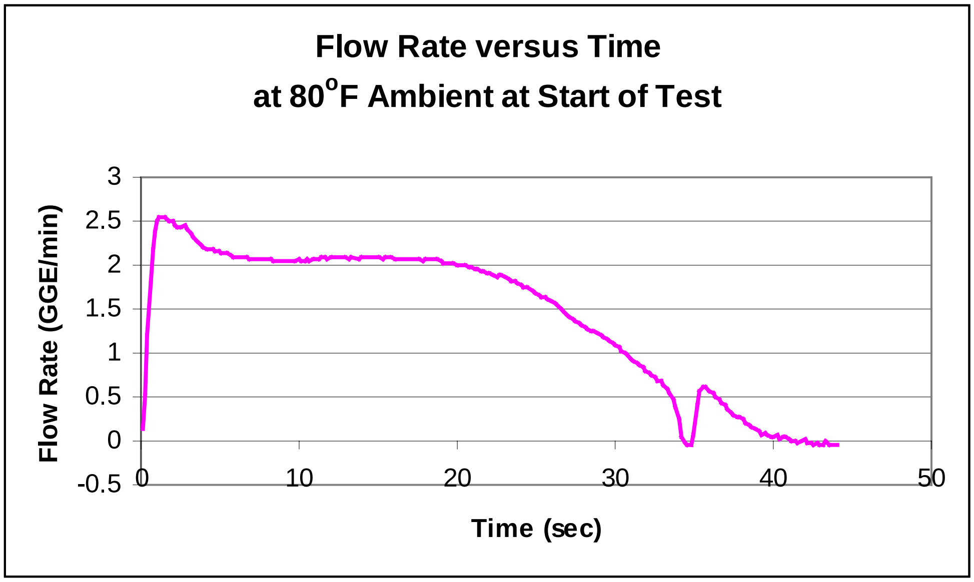


Figure 6.3-9 Flow Rate versus Time at 80°F Ambient at Start of Test.

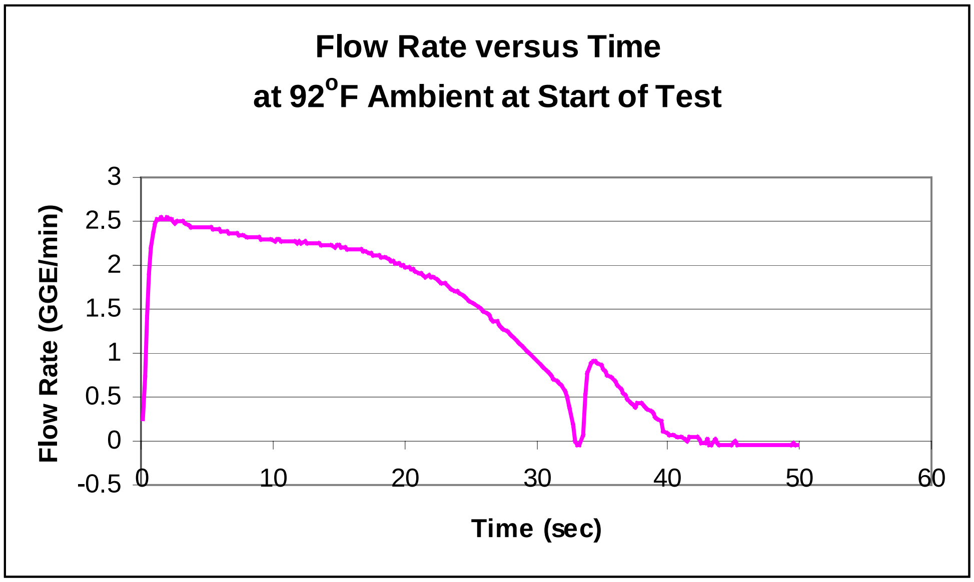


Figure 6.3-10 Flow Rate versus Time at 92^{o}F Ambient at Start of Test.

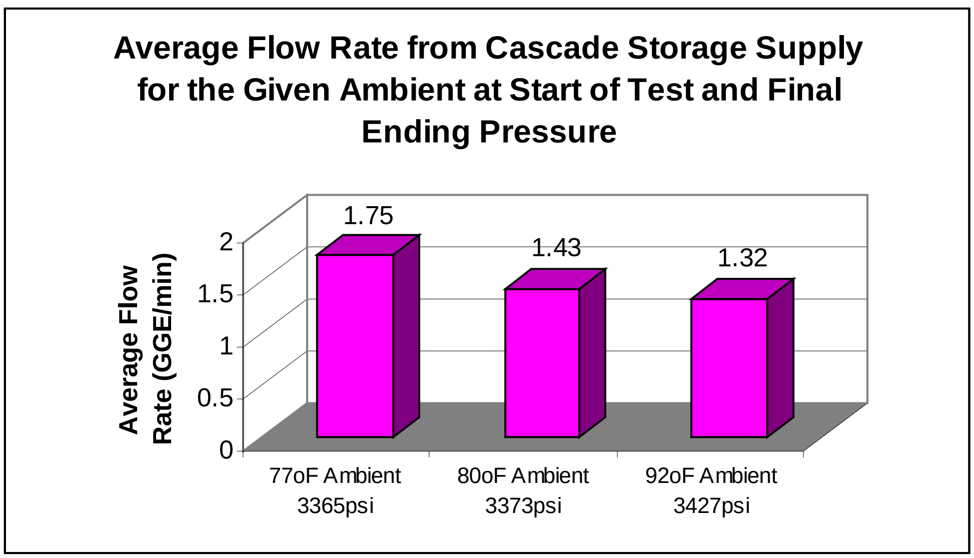


Figure 6.3-11 Average Flow Rate for Given Ambient and Final Pressure.

6.4 Pressure Drop Across Superior® Valve During the Fill Process

Pressure drops across the cylinder valve are important to know in order to understand in order to understand what parts of the CNG delivery system are restriction points of flow. The valve had a small pressure drop during the fill process. The pressure drops across the valve were approximately 0.08 psi at 46^{o}F ambient to 4.3 psi at 28^{o}F ambient for the single control volume system, and .17 psi at 80^{o}F ambient and .28 psi at 77^{o}F ambient for the cascade storage system. The aforementioned pressure drops are just the peak in magnitude of pressure drop during the fill process. The pressure drop appeared to be greatest during the initial stages of the fill process when the flow rate was at it’s highest during the initial surge of CNG into the test cylinder.

All of the tests compiled from the single control volume storage supply indicated that the pressure drop became negligible at approximately 10 seconds into the fill process except for the test compiled on the 28^{o}F ambient temperature day, which was the only test compiled below the freezing point of water. All tests compiled from the cascade system indicated that the pressure drop across the valve was negligible after approximately 10 seconds into the fill process.

6.4.1 Pressure Drop Across Cylinder Valve when CNG was Supplied from Single Volume Storage Supply.

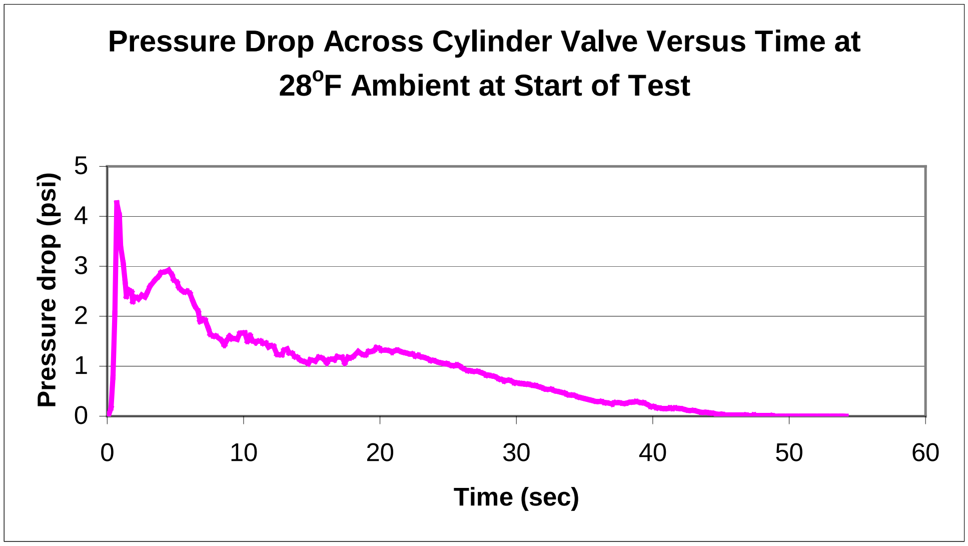


Figure 6.4-1 Pressure Drop Across Cylinder Valve Versus Time at 28°F Ambient at Start of Test.

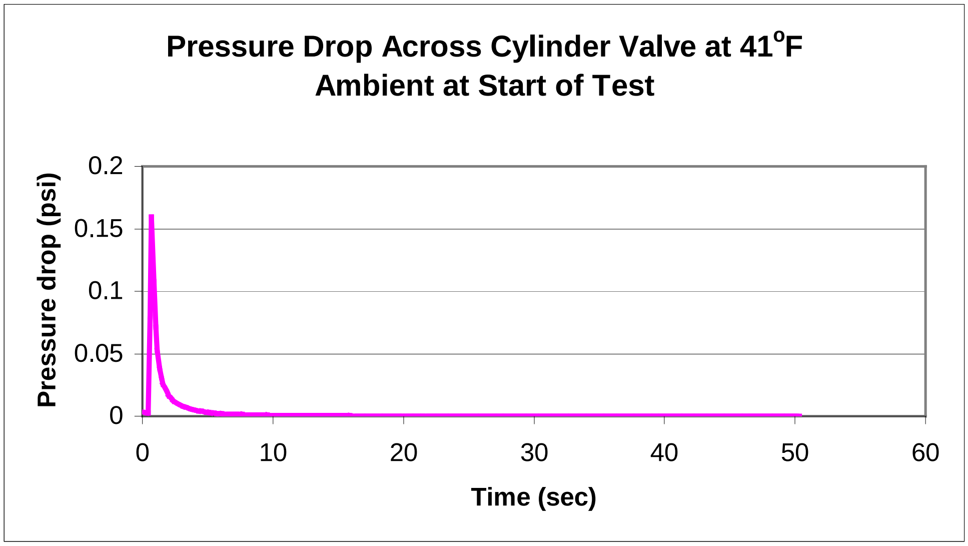


Figure 6.4-2 Pressure Drop Across Cylinder Valve at 41°F Ambient at Start of Test.

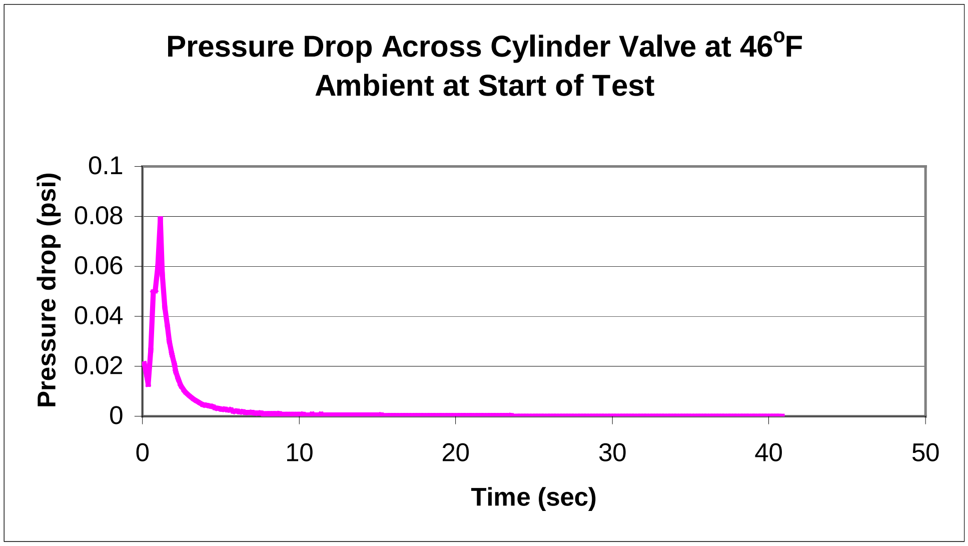


Figure 6.4-3 Pressure Drop Across Cylinder Valve at 46°F Ambient at Start of Test.

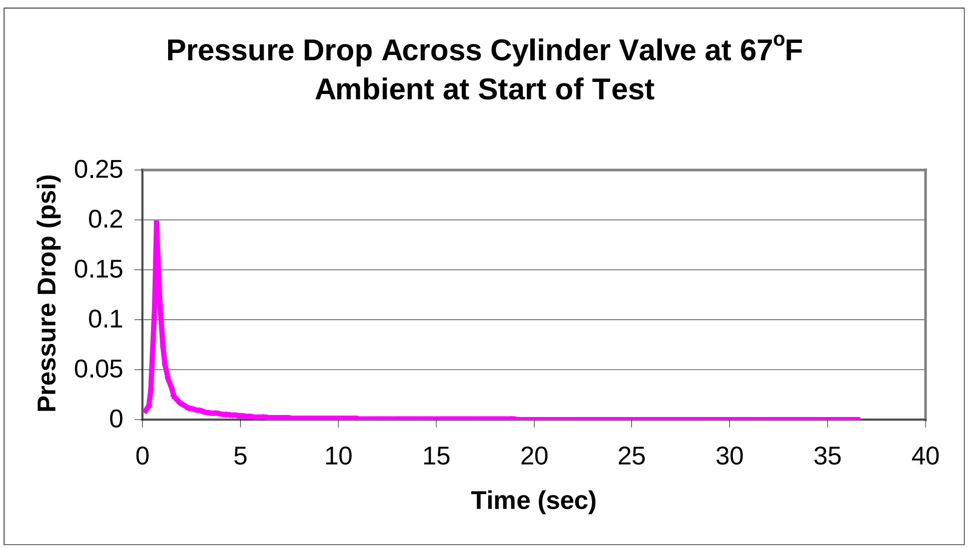


Figure 6.4-4 Pressure Drop Across Cylinder Valve at 67°F Ambient at Start of Test.

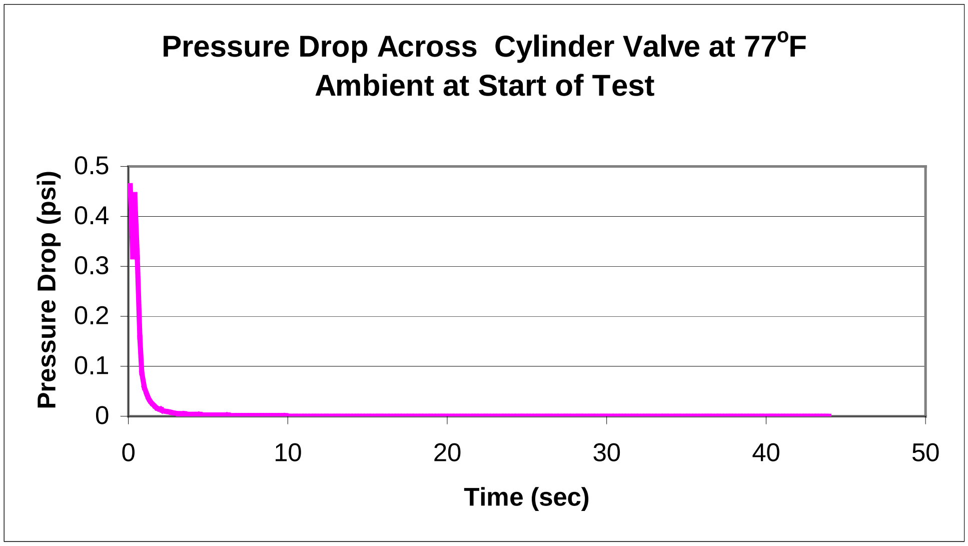


Figure 6.4-5 Pressure Drop Across Cylinder Valve at 77°F Ambient at Start of Test.

6.4.2 Pressure Drop Across Cylinder Valve when CNG was Supplied from the Cascade System.

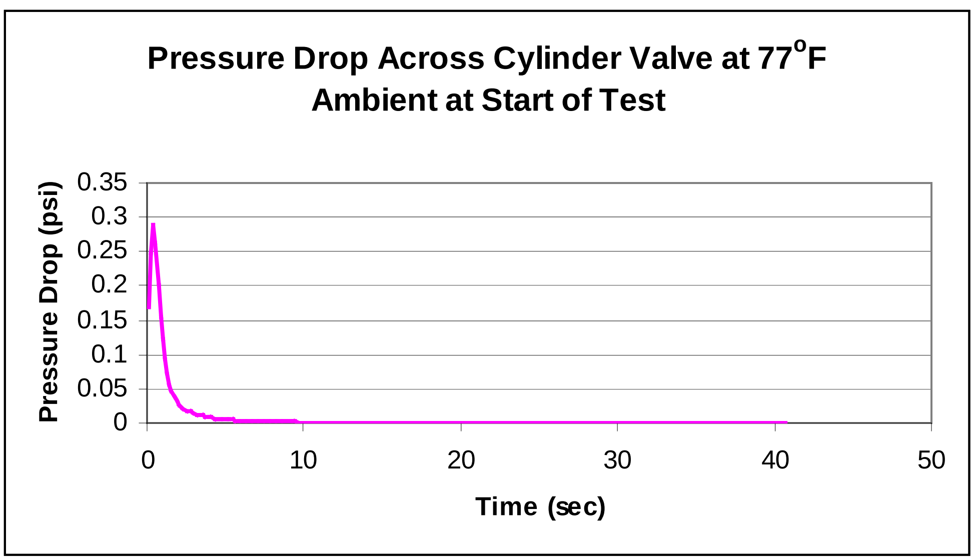


Figure 6.4-6 Pressure Drop Across Cylinder Valve at 77°F Ambient at Start of Test.

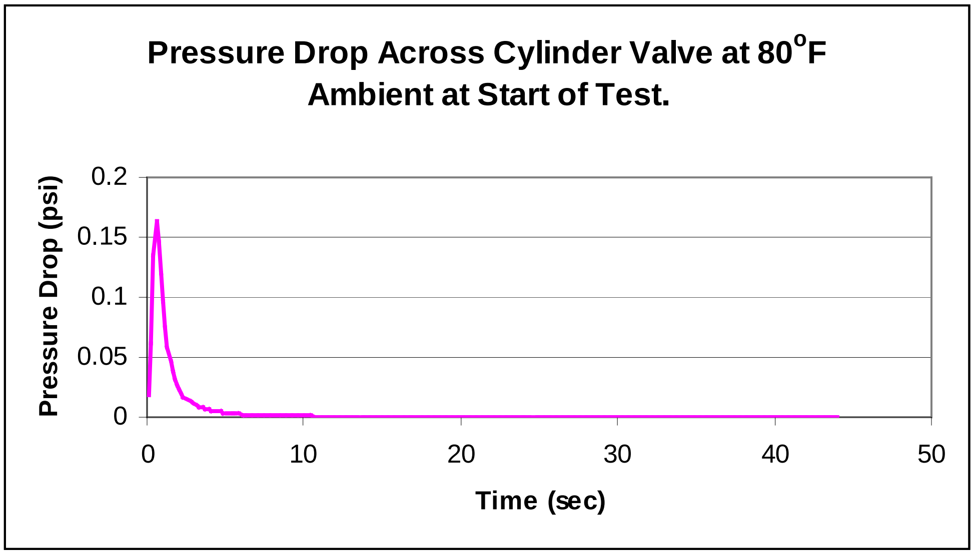


Figure 6.4-7 Pressure Drop Across Cylinder Valve at 80°F Ambient at Start of Test.

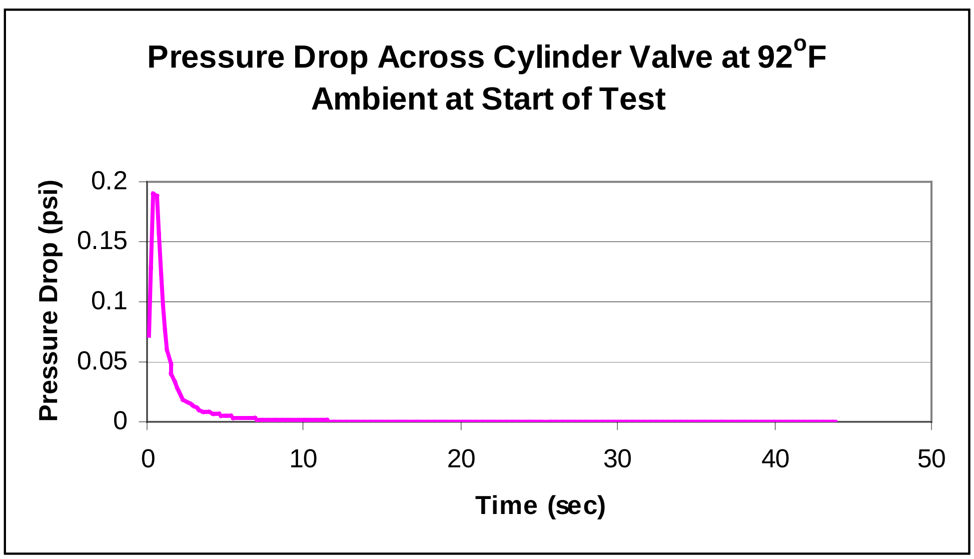


Figure 6.4-8 Pressure Drop Across Cylinder Valve at 92°F Ambient at Start of Test.

6.5 Total Volume of CNG Dispensed to Test Cylinder

As previously mentioned, the total volume dispensed to an NGV during the fast fill process very rarely reaches the 100% level without over pressurizing CNG storage system. This report provides confirmation that this is true. Even the best NGV refueling stations only guarantee a 92-98% fill level to the onboard CNG fuel storage system on an NGV. Not being able to guarantee a 100% fill level is not very desirable to future NGV consumers due to the already reduced driving range for an NGV, which is further reduced by not providing a 100% fill level. This report did not invent a method of providing this 100% fill level, rather a system to determine the total fill level (volume GGE) upon completion of the fast fill process which can help in the development of newer technology which may increase the chances of a 100% fill level. This report dealt with three methods of determining the total volume dispensed to the test cylinder: (1) simply recording the dispenser output, (2) thermodynamic relationship (section 4.2), and (3) integrating flow rate curve versus time (section 6.3).

All volume evaluations were compiled at the BP® refueling station (cascade type CNG storage system) in Westover, WV. The dispenser at the BP® refueling station (Figure 5.7-2) provided the total volume dispensed to a costumer in gasoline gallon equivalent (GGE). Natural gas (CNG) dispensers must be able to provide a +/- 1.5% actual volume displacement to the customer to follow NIST (National Institute of Standards and Technology) standards. Most public dispensers utilize a flow meter with a pulse output to determine the total volume displaced (positive displacement flowmeter).

The theoretical volume of CNG dispensed to the test cylinder was determined through the use of thermodynamic relationships utilizing Equation 4.2-1. The total mass of CNG dispensed to the test cylinder was calculated to determine the total theoretical GGE dispensed. Knowing that 1 GGE = 5.66 lb_m natural gas, this conversion factor can be applied to the total mass of CNG dispensed to determine the total GGE dispensed to the test cylinder. Equation 4.2-1 uses the final pressure (PX-41 pressure transducer) and the temperature (thermocouple/thermowell setup) of the fast fill process when solving for total mass of CNG dispensed. Section 4.2 illustrates all the factors taken into consideration to determine the total theoretical volume dispensed to the test cylinder. A final desired test cylinder pressure (3600 psi) and temperature (70^{o}F) was not met which immediately indicates that the desired 2 GGE fill level could not be met.

The flow meter and signal conditioner (section 5.3.6) was also used to determine total volume displaced. The flow meter and signal conditioner provided total volume dispensed through integrating the flow rate curve versus time (section 6.3). The volume found using this method, however, was on average approximately 25 % below the value that the dispenser provided. Since the integration method using the flow meter provided a volume 25% below actual volume (using dispenser value) on average, a correction factor was applied to 'raise' the volume dispensed to the test cylinder to display the actual volume dispensed. The reason the integration method was 25 % below dispenser value was because of the time lost to convert from a digital signal (from flow meter) to analog signal (signal conditioner 4-20 mA) back to digital (data acquisition card). This digital to analog to digital conversion process took too long to provide actual 'real time' data because of the time lag for the instrumentation to do the conversion. The manufacturer (Omega Engineering) of the flowmeter (FTB-933) suggested the use of a pulse output signal conditioner from the flow meter to provide real time data, but explained that if the integration method of the flow rate curve was consistently off by a certain factor (25 %) that it could be corrected to provide the actual volume displacement. The volume found using the flow rate integration method found the total volume dispensed by simply integrating the flow rate curve across the total time of any particular fast fill process observed, then applied the correction factor to determine the total volume dispensed. To use the correction factor, the total volume value found using the integration method was multiplied by .25 (25 %) then added to itself. For example, if the integration method provided a value of 100 GGE, it could be 'corrected' using the correction factor (100 GGE * .25 + 100 GGE = 125 GGE). Table 6.5-1 describes the methods used to determine the total volume dispensed to the test cylinder and the percent variation from the dispenser's readout of total volume.

The remainder of this section provides a graphical representation of the total volume dispensed to the test cylinder over three compiled tests. The total capacity of the test cylinder is 2 GGE at 3600 psi and 70 degrees F. The results illustrated graphically in Figure 6.5-1 indicate that the test cylinder was under filled every time, which is also described in Table 6.5-2. Figure 6.5-1 illustrates the volume dispensed via the dispenser readout, the theoretical value, and the flow rate integration method result. The bar graph illustrates the 2 GGE desired volume and the actual volume dispensed to the test cylinder using the methods previously mentioned. Notice that all three cases report a fill volume below the desired 2 GGE.

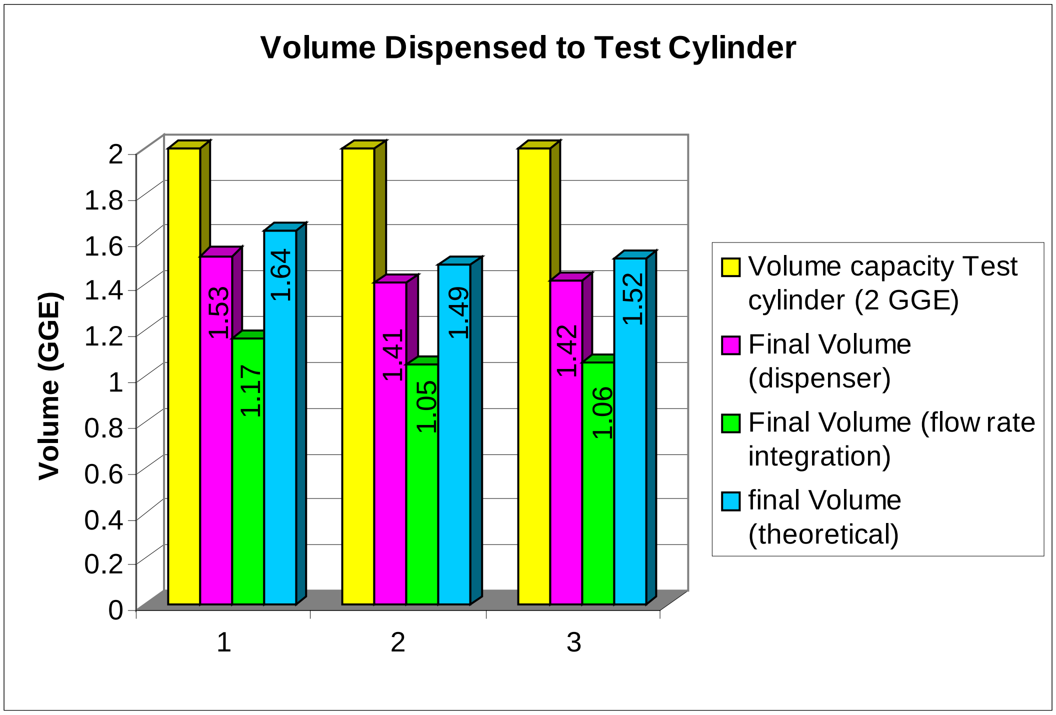


Figure 6.5-1 Graphical Illustration of Volume of CNG Dispensed to the Test Cylinder.

Test #	*Volume (GGE) Dispenser Readout*	*Volume (GGE) Flow Rate Integration over Time (before application of correction factor)*	*% Variation of integration method from Dispenser Readout*	*Volume (GGE) Theoretical*	*% Variation of theoretical method from Dispenser Readout*
1	*1.53*	*1.17*	*-24*	*1.64*	*+7*
2	*1.41*	*1.05*	*-25*	*1.49*	*+6*
3	*1.42*	*1.06*	*-25*	*1.52*	*+7*

Table 6.5-1 Volume percent variation from dispenser readout.

Test #	***Total Capacity (GGE)***	***Volume (GGE) from Dispenser Readout***	***Final Pressure (psi) of Test Cylinder***	***Final Temperature (^oF) of Test Cylinder***	***% under desired volume fill level of 100%***
1	2	1.53	3365	102	-23.5
2	2	1.41	3356	132	-29.5
3	2	1.42	3530	141	-29.0

Table 6.5-2 Percent under desired fill level of 100%

7 Conclusions and Recommendations

7.1 Conclusions

The transportable experimental testing apparatus provided the desired information for the fast fill process. The desired information was temperature, pressure, flow rate, and volume. The information collected indicates that ambient temperature change can have an affect on the fast fill process as illustrated throughout chapter 6. The information provided by the testing apparatus also concluded that, as expected, the test cylinder was under filled every time it was rapidly recharged (section 6.5). The desired fill level of 2 GGE at 3600 psi and 70^{o}F was not supplied by either facility in which tests were compiled. As mentioned, this report does not intend to invent a new method of guaranteeing a 100% fill level to an NGV, but to provide a system to analyze any particular fast fill compressor station that is already online which may be able to aid in future NGV refueling station technology. All tests were compiled from the rapid charge of an empty or nearly empty test cylinder.

7.2 Recommendations

All tests were performed outdoors at the WVU physical plant and the BP® station using a desk top computer. Tests were performed at different outdoor temperature days to depict the effects of ambient temperature changes. All data was correct, even though some of may have been slightly 'off' due to solar radiation affects.

Although the test system does depict the effects of ambient temperature change on the fast fill process, it does not always take into account the 'exact' ambient temperature. Solar effects may have been present. An example of a solar effect could be if a test was executed late in the morning on a spring day. CNG in the refueling station storage system may have dropped to a very cold temperature through out the night due to drop in ambient temperature throughout the night. The next morning the temperature rises significantly in a short period of time, however, the temperature of CNG in the storage system is lagging behind slightly. Or, if the storage system was shaded it would have a huge affect if the temperature was rapidly rising and it was sunny. This could cause the storage CNG to be different from the ambient even though they are continuously surrounded by a common ambient temperature. If the test apparatus was not set up in the shade on one of those days the data could be slightly incorrect. That is just one example of solar affects effecting the data. A thermally controlled experimental test lab containing the entire system with an known equilibrium temperature in the storage cylinders and the receiving CNG cylinder would better depict the exact effect of ambient temperature change on the fast fill process.

A desktop computer was utilized for the research testing compiled for this report. The desktop computer worked perfectly for its role in collecting data, however, it was large, awkward, and inconvenient to transport. A lap top computer with a PCMCIA DAQ card would also work perfectly to collect data and eliminate the awkwardness and inconvenience of transporting a desktop computer to collect data. A laptop computer would be a more sensible choice while compiling field as in this report.

A digital pulse output signal conditioner mounted on the FTB-933 flow meter would be a more precise method to determine total volume dispensed to the test cylinder or to an NGV. The pulse output signal conditioner would provide real time volume accumulation information. But, in order to observe flow rate and pulse output at the same time during the fill, a second flow meter would have to be purchased. One flow meter would have the 4-20 mA output (flow rate) and the other would have the pulse output (volume accumulation).

Appendix A

```
'This program written by: Eric Shipley
'This is a QBASIC PROGRAM that will read voltages from an RTI-815 board
to display: pressure, temperature, and flow rate.

 CLS

 X = 0

SCFM = -20

'***************CODED TRIGGER TO BEGIN TAKING DATA********************

DO UNTIL SCFM >= 0

N = 0
TEMPF = 0
P = 0
PRESSF = 0
F = 0
FLOWF = 0

'*********TEMPERATURE READING SECTION**************

DO UNTIL N = 1000
OUT 769, 1
OUT 770, 1
TEMPI = INP(771)
TEMP2 = INP(772)
NUM = TEMP2 * 256 + TEMPI
VOLTS = (-5 + (10 / 4095) * NUM)
TEMP = VOLTS / .001
TEMPF = TEMPF + TEMP
N = N + I
LOOP

'************Pressure Reading Section**************

DO UNTIL P = 1000
OUT 769, 2
OUT 770, 1
PRESSI = INP(771)
PRESS2 = INP(772)
SCALE = PRESS2 * 256 + PRESSI
PERCENT = SCALE / 4095
VOLTAGE = -6 + 10  *  PERCENT
```

```
PRESSURE = VOLTAGE * (5000 / 4)
PRESSF = PRESSF + PRESSURE
P = P + I
LOOP

'***************FLOW RATE READING SECTION******************

DO UNTIL F = 1000
OUT 769, 3
OUT 770, 1
FLOW1 = INP(771)
FLOW2 = INP(772)
SCALE = FLOW2 * 256 + FLOWI
PERCENT = SCALE / 4095
VOLTAGE = -6 + 10 * PERCENT
FLOW = (7.85 / 4) * VOLTAGE
FLOWF = FLOWF + FLOW
F = F + I
LOOP

TEMP2 = TEMPF / N
PRESS2 = PRESSF / P
FLOW2 = FLOWF / F

'CALCULATES THE STANDARD CUBIC FEET PER MINUTE OF THE CH4
SCFM = FLOW2 / ((14.7 / (PRESS2 + 14-7)) * ((TEMP2 + 460)      530))

LOOP

'**************************************************
'**************************************************
'***********THE TRIGGER HAS BEEN EXECUTED; THE DATA WILL NOW BE
RECORDED

OPEN "GASPUMP2.DAT" FOR OUTPUT AS #1

PRINT "THE DATE THAT THIS DATA WAS COLLECTED:"; DATE$
PRINT "THE TIME OF THE DAY THE DATA WAS COLLECTED:"; TIME$
PRINT ""
PRINT "THIS PROGRAM WILL DISPLAY TEMPERATURE, PRESSURE, AND
FLOWRATE"
PRINT ""
PRINT
"***************************************************************************
**************************************"
PRINT PRINT "SAMPLE     TIME ELAPSED(SEC)     TEMPERATURE(F)    PRESSURE(PSI)
FLOW(SCFM

X = 0
START = TIMER
```

```
DO UNTIL SCFM <= 0

N = 0
TEMPF = 0
P = 0
PRESSF = 0
F = 0
FLOWF = 0
K = 0
TANKTEMPF = 0

'**********TEMPERATURE READING SECTION***************

DO UNTIL N = 1000
OUT 769, 1
OUT 770, 1
TEMPI = INP(771)
TEMP2 = INP(772)
NUM = TEMP2 * 256 + TEMPI
VOLTS = (-5 + (10 / 4095)    NUM)
TEMP = VOLTS / .001
TEMPF = TEMPF + TEMP
N = N + I
LOOP

'*************Pressure Reading Section***************

DO UNTIL P = 1000
OUT 769, 2
OUT 770, 1
PRESSI = INP(771)
PRESS2 = INP(772)
SCALE = PRESS2 * 256 + PRESSI
PERCENT = SCALE / 4095
VOLTAGE = -6 + 10 * PERCENT
PRESSURE = VOLTAGE * (5000 / 4)
PRESSF = PRESSF + PRESSURE
P = P + I
LOOP

'***************FLOW RATE READING SECTION******************

DO UNTIL F = 1000
OUT 769, 3
OUT 770, 1
FLOWI = INP(771)
FLOW2 = INP(772)
SCALE = FLOW2 * 256 + FLOWI
PERCENT = SCALE / 4095
VOLTAGE = -6 + 10 * PERCENT
FLOW = (7.85 / 4) * VOLTAGE
```

```
FLOWF   FLOWF + FLOW
F = F + I
LOOP

'***************TANK; INTERNAL TEMPERATURE READING SECTION********

DO UNTIL K = 1000
OUT 769, 4
OUT 770, 1
TANKTEMPI = INP(771)
TANKTEMP2 = INP(772)
NUM = TANKTEMP2 * 256 + TANKTEMP1
VOLTS = (-5 + (10 / 4095) * NUM)
TANKTEMP = VOLTS / .001
TANKTEMPF = TANKTEMPF + TANKTEMP
K = K + I
LOOP

'***************FINAL CALCULATIONS TO DISPLAY OUTPUT********

FINISH! = TIMER
TEMP2 = TEMPF / N
PRESS2 = PRESSF / P
FLOW2 = FLOWF / F
TANKTEMP2 = TANKTEMPF / K

'CALCULATES THE STANDARD CUBIC FEET PER MINUTE OF THE CH4
SCFM = FLOW2 / ((14.7 / (PRESS2 + 14.7)) * ((TEMP2 + 460) / 530))

X = X + I
T= FINISH - START

PRINT T, TEMP2, PRESS2, SCFM, TANKTEMP2
PRINT #1 T, TEMP2, PRESS2, SCFM, TANKTEMP2

LOOP

CLOSE #1
```

Appendix B

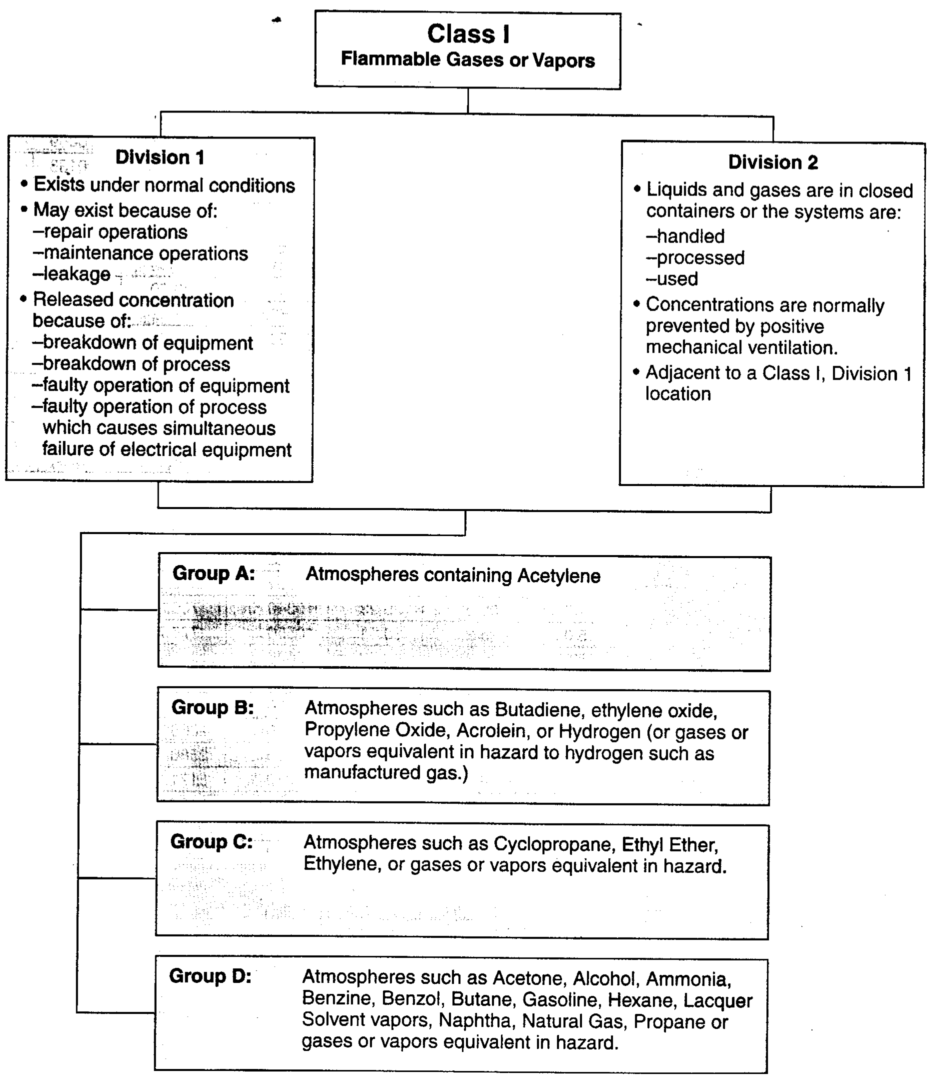
```
c$NOTRUNCATE
C
C     THIS ROUTINE COMPUTES DENSITY OF MEAN U.S. GAS MIXTURE, FOR GIVEN
C     PRESSURE AND TEMERATURE (PRESSURE RANGE: 14.7-5000 PSIA)
C     UNITS:      P     PSIA
C                 T     F
C               RHO     LBM/FT**3
C
      DIMENSION A0(5),A1(5),A2(5),A3(5),A4(5),A5(5),A6(5),A7(5),A8(5)
      DATA A0/-.2994295E+00,-.3343221E+01,-.2628989E+02,+.3092211E+02,
     &-.6128675E-02/
      DATA A1/-.3487948E-02,-.1842292E-01,-.5661105E-01,+.3983686E-02,
     &-.4368347E-03/
      DATA A2/+.8219936E-03,+.1352748E-01,+.8513020E-01,-.1486127E+00,
     &+.2088281E-04/
      DATA A3/+.3162543E+01,+.5992787E+01,+.1877627E+02,+.6835460E+01,
     &+.1742212E+01/
      DATA A4/-.1058533E+01,+.5557355E+00,+.2854977E+00,-.6623889E+00,
     &+.2014086E+00/
      DATA A5/+.8145651E+00,+.1126193E-01,-.5140347E-01,+.1701009E-01,
     &+.2001732E+00/
      DATA A6/+.9307038E-06,-.1638089E-05,+.6831632E-06,+.6680183E-06,
     &-.4553512E-06/
      DATA A7/-.6011406E-06,-.1360555E-04,-.6458707E-04,+.1462390E-03,
     &-.1761429E-07/
      DATA A8/+.2192528E-05,+.1921265E-04,+.4269540E-04,-.1280760E-04,
     &+.3721930E-06/

      open(1,file='cascade2.txt')
      open(2,file='cas_rho.txt')
      do i=1,214
      read(1,*) id,t,p


      IF (P.GT.5000) THEN
        WRITE (*,*) 'PRESSURE > 5000 PSIA IN SUBR GASDEN, P=',P
        WRITE (*,*) 'PROGRAM STOPS'
        STOP
      ENDIF
      IF (P.GE.100..AND.P.LT.300.) J=1
      IF (P.GE.300..AND.P.LT.1000.) J=2
      IF (P.GE.1000..AND.P.LT.2500.) J=3
      IF (P.GE.2500..AND.P.LE.5000.) J=4
      IF (P.LT.100.) J=5
      X1=P
      X2=T+459.6
      X3=X1/X2
      X4=X3*X3
      X5=X3*X4
      X6=X1**2
```

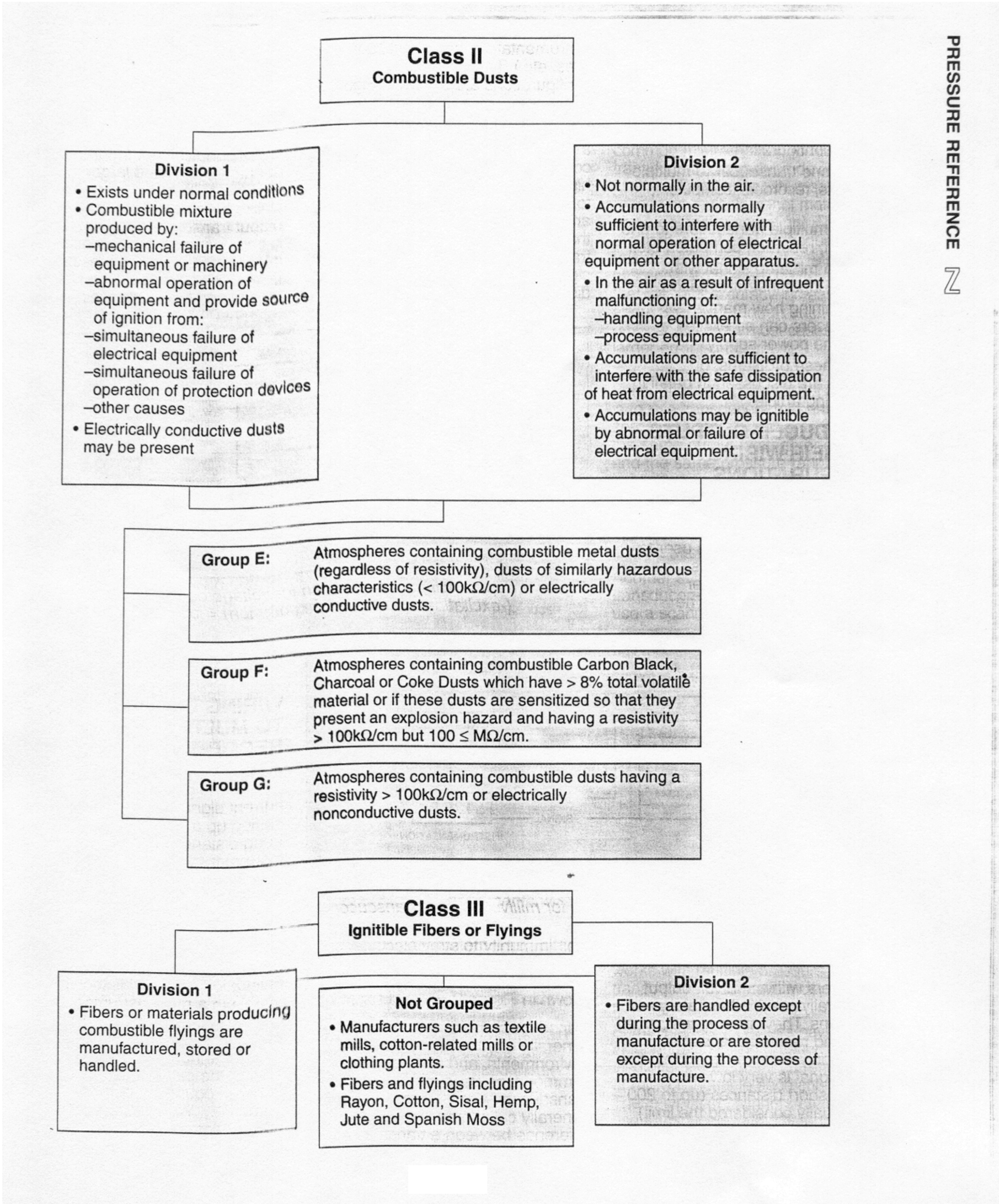
```
      X7=X2**2
      X8=X1*X2
      RHO=A0(J)+A1(J)*X1+A2(J)*X2+A3(J)*X3+A4(J)*X4
      RHO=RHO+  A5(J)*X5+A6(J)*X6+A7(J)*X7+A8(J)*X8

      write(2,*) id, rho
      enddo
c      RETURN
      END
```

Appendix C

INTRINSIC SAFETY

Hazardous (Classified) Locations in Accordance with Article 500, National Electrical Code–1990




PRESSURE REFERENCE
Class II
Combustible Dusts
Division 1
• Exists under normal conditions
• Combustible mixture produced by:
–mechanical failure of equipment or machinery
–abnormal operation of equipment and provide source of ignition from:
–simultaneous failure of electrical equipment
–simultaneous failure of operation of protection devices
–other causes
• Electrically conductive dusts may be present
Division 2
• Not normally in the air.
• Accumulations normally sufficient to interfere with normal operation of electrical equipment or other apparatus.
• In the air as a result of infrequent malfunctioning of:
–handling equipment
–process equipment
• Accumulations are sufficient to interfere with the safe dissipation of heat from electrical equipment.
• Accumulations may be ignitible by abnormal or failure of electrical equipment.
Group E:
Atmospheres containing combustible metal dusts (regardless of resistivity), dusts of similarly hazardous characteristics (< 100kΩ/cm) or electrically conductive dusts.
Group F:
Atmospheres containing combustible Carbon Black, Charcoal or Coke Dusts which have > 8% total volatile material or if these dusts are sensitized so that they present an explosion hazard and having a resistivity > 100kΩ/cm but 100 ≤ MΩ/cm.
Group G:
Atmospheres containing combustible dusts having a resistivity > 100kΩ/cm or electrically nonconductive dusts.
Class III
Ignitible Fibers or Flyings
Division 1
• Fibers or materials producing combustible flyings are manufactured, stored or handled.
Not Grouped
• Manufacturers such as textile mills, cotton-related mills or clothing plants.
• Fibers and flyings including Rayon, Cotton, Sisal, Hemp, Jute and Spanish Moss
Division 2
• Fibers are handled except during the process of manufacture or are stored except during the process of manufacture.

3 TYPICAL METERING RUNS

METERING LOCATION

UPSTREAM

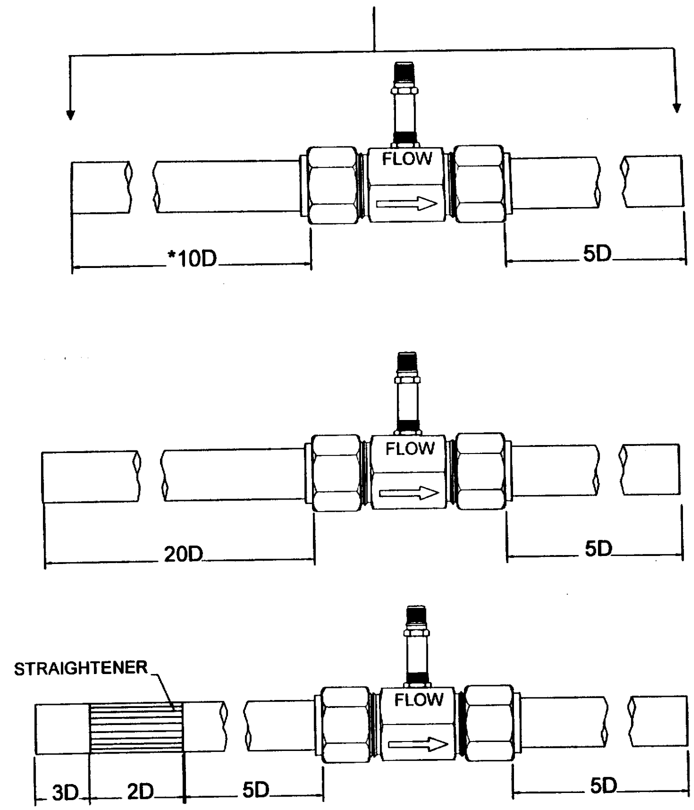
Pipe fitting immediately preceding metering location

Wide open valve (gate or plug)
or
Sharp right angle bend
(mitered elbow)
or
straight run of pipe

DOWNSTREAM

Pipe fitting immediately following metering location.

Any fitting, valve or pipe run



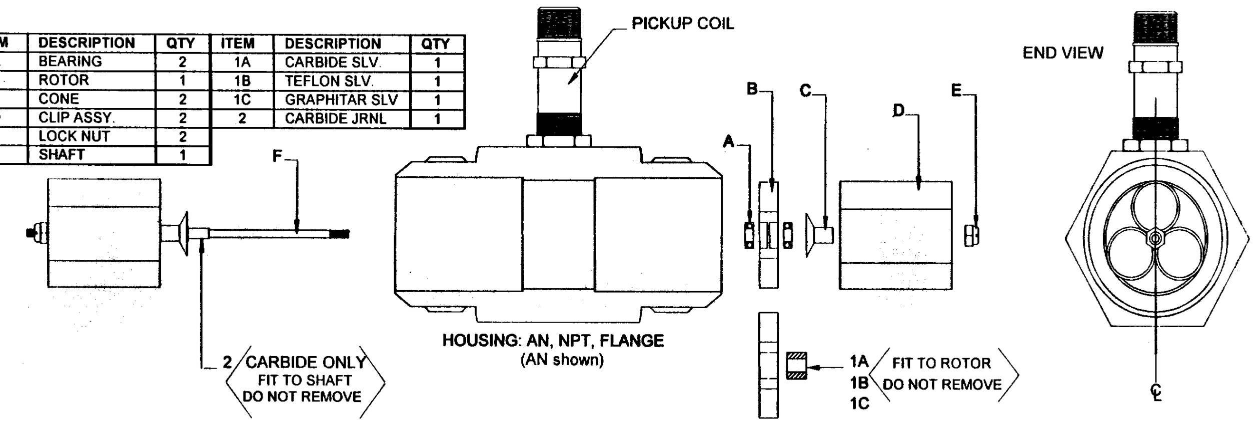
Long radius bends
or
smooth elbows
or
two elbows
or
partially open valves
of any type

Any fitting, valve or pipe run

*Minimum lengths of straight pipe required expressed in nominal pipe diameters.

FIGURE 2: FTB-900 SERIES PRECISION TURBINE FLOWMETER

ITEM	DESCRIPTION	QTY	ITEM	DESCRIPTION	QTY
A	BEARING	2	1A	CARBIDE SLV.	1
B	ROTOR	1	1B	TEFLON SLV.	1
C	CONE	2	1C	GRAPHITAR SLV	1
D	CLIP ASSY.	2	2	CARBIDE JRNL	1
E	LOCK NUT	2			
F	SHAFT	1			



DISASSEMBLY FOR 1/2" AND LARGER METERS		REASSEMBLY FOR 1/2" AND LARGER METERS	
STD: FOR BALL BEARING	OPT: FOR SLEEVED BEARING	STD: FOR BALL BEARING	OPT: FOR SLEEVED BEARING
1. Remove lock nut from shaft end marked "IN". 2. Insert extraction hook into "IN" clip assembly and extract with a parallel pulling motion. 3. Remove cone, bearings and rotor. 4. Remove "OUT" clip assembly with extraction hook as directed in step 2. DO NOT remove lock nut. Leave clip, cone, shaft and nut assembled. (Refer to diagram)	Before beginning: Assembly must go back together the exact way it comes out. 1. Remove lock nut from shaft end marked "IN". 2. Insert extraction hook into "IN" clip assembly and extract with a parallel pulling motion. 3. Remove cone and rotor. DO NOT attempt to remove bearing from rotor. 4. Remove "OUT" clip assembly with extraction hook as directed in step 2. DO NOT remove lock nut. Leave clip, cone, shaft and nut assembled. (Refer to diagram)	NOTE: If any part appears damaged "DO NOT REASSEMBLE". Call Flow Dept. for instructions 1. Place meter on table vertically, "OUT" side upward. 2. Insert "OUT" clip/cone/shaft/nut assembly into housing as illustrated in endview diagram, push down as far as it will go (seating against step in housing) Clip bundle diameter may need to be clamped for easier insertion. 3. Flip meter around and insert bearing (open side down), rotor, bearing (open side up), then cone. Be sure the "IN" marking on the rotor coincides with the "IN" marking on the housing. 4. Insert "IN" clip assembly. 5. Screw on lock nut snug against "IN" clip assembly. **DO NOT OVER TIGHTEN**.	NOTE: If any part appears damaged **DO NOT REASSEMBLE**. Call Flow Dept. for instructions 1. Place meter on table vertically, "OUT" side upward. 2. Insert "OUT" clip/cone/shaft/nut assembly into housing as illustrated in endview diagram, push down as far as it will go (seating against step in housing) Clip bundle diameter may need to be clamped for easier insertion. 3. Flip meter around and insert rotor with bearing , then cone. Be sure the "IN" marking on the rotor coincides with the "IN" marking on the housing. 4. Insert "IN" clip assembly. 5. Screw on lock nut snug against "IN" clip assembly. **DO NOT OVER TIGHTEN**.

8 References

[1] The Natural Gas Vehicle Coalition (NGVC), "Environmental Benefits", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/environmentalbenefits.html, 2002.

[2] The Natural Gas Vehicle Coalition (NGVC), "Environmental Benefits", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/ngvmessage.html, 2002.

[3] The Natural Gas Vehicle Coalition (NGVC), "Environmental and Health Benefits", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/fastfacts.html, 2002.

[4] The Natural Gas Vehicle Coalition (NGVC), "The NGV Message", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/ngvmessage.html, 2002.

[5] The Natural Gas Vehicle Coalition (NGVC), "Clean Efficient Automobiles Resulting from Advanced Car Technologies (Clear Act)", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/CLEARACTsummary.html, 2002.

[6] The Natural Gas Vehicle Coalition (NGVC), "Clean Efficient Automobiles Resulting from Advanced Car Technologies (Clear Act)", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/CLEARACTsummary.html, 2002.

[7] Barajas, Andre M., et al, "NGV Fueling Station Technology Program", Southwest Engineering Institute, San Antonio, TX, 1997, page1.

[8] The Natural Gas Vehicle Coalition (NGVC), "Clean Efficient Automobiles Resulting from Advanced Car Technologies (Clear Act)", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/CLEARACTsummary.html, 2002.

[9] The Natural Gas Vehicle Coalition (NGVC), "Benefits of NGV's", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/fastfacts.html, 2002.

[10] The Natural Gas Vehicle Coalition (NGVC), "Natural Gas Vehicles: The Environmental Solution Now", http://www.ngvc.org/ngv/ngvc.nsf/bytitle/environmentalbenefits.html, 2002.

[11] The Alternative Fuels Data Center (AFDC), "Alternative Fuel Station Locator", http://www.afdc.doe.gov/altfuel/cng.html, 2002.

[12] U.S. Dept. of Energy (DOE) and U.S. Environmental Protection Agency (EPA), "Find and Compare Cars", http://www.fueleconomy.gov/, 2002.

[13] Barajas, Andre M., et al, "NGV Fueling Station Technology Program", Southwest Engineering Institute, San Antonio, TX, 1997, page1.

[14] Kountz, Kenneth J., "Modeling the Fast Fill Process in Natural Gas Vehicle Storage Cylinders", Institute of Gas Technology, Chicago, IL, 1994, pp 1-4.

[15] Kountz, Kenneth K., Blazek, Christopher F., "NGV Fueling Station and Dispenser Control Systems", Institute of Gas Technology, Des Plaines, IL, 1997, page 1.

[16] Hutton, Jerrold, "Compressed Natural Gas Vehicle Conversion", Hocking Technical College, 1984, page120.

[17] Kountz, Kenneth J., “Natural Gas Storage Conditions as a Function of Operating Environment”, Institute of Gas Technology Energy Development Center, Chicago, IL, 1996, page20.

[18] Wark, Kenneth Jr., et al., “Advanced Thermodynamics for Engineers”, McGraw Hill, Boston, Massachusetts, 1995, pages 166-167.

[19] Beckwith, Thomas G., Marangoni, Roy D., Lienhard V, John H., “Mechanical Measurements: Fifth Edition”, Addison-Wesley Publishing Company, page 82, 1993.

[20] The International Society for Measurement and Control (ISA), “Intrinsic Safety-for Omega Engineering Flow Handbook”, Research Triangle Park, NC, page K-107, 2000.

[21] Omega Engineering, “Turbine and Paddlewheel Flowmeters-Flow Book”, Stamford, CT, 2000, page F-3.

[22] Omega Engineering, “Economical Ball Bearing Gas Turbine Flowmeters”, Stamford, CT, 2000, page F-17B.

[23] Advanced Technical Products Inc., “Tuffshell® All-Composite NGV Fuel Tank”, Lincoln, NE, 2001.

[24] Omega Engineering “Omegatherm® Thermally Conductive Silicon Paste”, Stamford, CT, 1999.

[25] Doebelin, Ernest O., “Measurement Systems Application and Design Third Edition”, McGraw-Hill Book Company, New York, pp.112-113, 1983.

[26] Lyons, Jerry L., Askland, Carl L. Jr., “Lyons Encyclopedia of Valves”, Van Nostrand Reinhold Company, New York, page 90, 1975.

[27] Yeremian, J., “Analysis of Vehicle Refueling Parameters,” Final Report, Canadian Gas Association, Project NGV 200-5.19, April 1993.

[28] Neilson, J.B., G. Cripps, and C. Webster, “Review of Certification and Approval Requirements for Electronic NGV Dispensers,” Final Report, Canadian Gas Association, Project NGV 200-1.15, June 1992.

[29] Dowling, Ralph O., “Cascade Basics”, RP Publishing, Denver, CO, pp28-31, 1993.

[30] Moran, Michael J., Shapiro, Howard N., “Fundamentals of Engineering Thermodynamics”, John Wiley and Sons Inc., New York, pp. 488-449, 1999.